REPORT ON

MOBILE OFFSHORE DRILLING UNIT

DESIGN EVOLUTION

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Table of Contents

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1. INTRODUCTION

1.1 BACKGROUND

This report presents a summary and evaluation of various technological advancements in the evolution of mobile offshore drilling unit (MODU) design. The main objectives of this report are to present a concise summary of the following information to the Royal Commission on the Ocean Ranger Marine Disaster:

1. Historical summary of MODU design evolution.

2. Historical perspective of early and modern MODU design features.

3. Development of design procedures for principal systems and features.

4. Identification of major technological advancements.

5. Assessment of overall increase in the level of safety.

6. Assessment of changes in technology related to more severe operating environments.

Published technical articles and studies are used together with the authors' experience in design of MODUs as a basis for the findings provided. Published information is identified in the list of references.

1.2 SCOPE OF STUDY

The study concentrates on the design of jack-up, ship-shaped, and semisubmersible drilling units. A typical configuration of each is shown in Figures 1 to 3 respectively. Other early types are discussed in the historical review. The chronological investigation is assumed to span the period from the 1940's to the present, or approximately 40 years, with emphasis on the period from the mid 1970's to the present. The design review includes only the principal elements and features of the platforms, such as hull configuration, structural arrangement, ballast system, stability aspects, mooring, ship's service and lifesaving systems, instrumentation and control systems, and severe environment considerations. Drilling systems and related equipment such as the Blowout Preventer (BOP) and riser handling systems, derrick, and substructure design are not included in this study, except as discussed briefly in Section 3.2.

1.3 ORGANIZATION

The report is arranged in three basic parts. The first part is made up of Sections 1 through 3 comprising the Introduction, Summary, and a General Review of Rig Design. The second part -- Systems Review, discusses the development of the key systems of offshore drilling units in Section 4. Section 5 makes up the third part of this paper, covering the design process, including procedures and state of the art techniques used in the design of MODU's. Figures and references are given in Sections 6 and 7, respectively. A short glossary of terms is provided in Section 8.

2. SUMMARY

2.1 MAJOR DEVELOPMENTS IN DESIGN CONCEPTS

The evaluation of MODU designs over the past 40 years has been highlighted by the following design developments:

2.1.1 Semisubmersible Configuration

The semisubmersible MODU configuration has evolved as the most practical compromise for performing in harsh environments. Modern units are able to carry deckloads in excess of 4,000 ST, to drill wells in excess of 25,000 ft deep, while operating moored in water depths up to 1,500 ft, or while dynamically positioned in water up to 6,000 ft deep. The semisubmersible configuration has the greatest overall operability of the different MODU types.

2.1.2 Mooring Systems

For a long time, MODU mooring systems were limited to water depths of 600 ft or less. In the 1970's winch capacities and chain and wire manufacturing techniques were improved to permit mooring systems to be designed for depths up to 1,500 ft. Water depth extensions have increased the weight of mooring systems dramatically, leading to novel arrangements of mooring components, including conventional chain and windlass systems, combination chain and wire systems, and all-wire systems with drum winches. Each of these systems involved some compromise on payload versus depth capability. One novel approach was the development of the turret mooring system based on existing mooring technology. This system allowed drill ships to attain higher operability by permitting the vessel to change its heading to minimize motions.

In the past 5 years a number of semisubmersible units have incorporated dynamic positioning systems to eliminate water depth limitations. The reliability and controlability of modern thrusters

gives dynamically stationed MODUs the capability to drill in water over 4,000 ft deep and in storms up to Force 9/10.

2.1.3 Structural Arrangement

The most efficient structural arrangement has been the twin-hull semisubmersible, comprised of two pontoons supporting 4, 6, or 8 stability columns and deck structure. Columns and hulls are tied together by transverse and longitudinal tubular truss arrangements. The upper deck may be a single level platform or it may be a two-level barge or 'box' deck to gain topside space. The single deck configuration offers lower topsides weight and greater deck load capability, while the barge deck configuration can provide reserve buoyancy in the event of extreme list.

2.1.4 Materials and Welding

The principal developments in the area of material selection for MODUs have been the introduction of higher-strength steels, low-temperature notch-toughened steels, and through-thickness steels used in high stress areas particularly in connections.

Higher strength steels were first recognized in shipbuilding practice in the 1960's, and these were eventually included in most classification society rules by the early 1970's. The latest classification rules now address selection criteria based on service application.

Welding techniques have advanced in the areas of pre and post-heat treatment, development of procedures for welding large thicknesses, and welding of high-strength low alloy steels. Principal achievements have been in reduction of pre-heat and post-heat requirements and in increasing weld deposition rates to achieve greater fabrication productivity.

2.1.5 Ballast Systems

Present day semisubmersible MODUs have efficient, remote controlled ballast systems capable of trimming or changing the draft of the unit quickly and accurately. These systems evolved from the early gravity fill independent tank systems to todays positive-fill redundant systems.

Early jack-up units had no system which could be considered a ballast system. These units had individual leg or corner pre-load tanks. Present generation jack-ups have bilge drain systems and pre-load tanks under centralized control. This allows better control of the critical loading and unloading of the legs.

2.1.6 Ballast Control Station

Early MODUs, particularly jack-ups, had no centralized control location for ballast pumps, and ballast control was dependent on coordination of operations among several local stations. Modern MODUs have taken advantage of sophisticated control technology now available to provide complete control of the ballasting function from a central location. Semisubmersible MODUs incorporate central ballast control boards containing tank level, valve status, draft status and pump control information in 'mimic' layout.

2.1.7 Propulsion System

Most early MODU designs were not self-propelled, with the exception of drill ships, which utilized conventional ship propulsion systems. Tunnel thrusters were introduced in drill ships to provide some lateral assistance for conventional mooring systems, and gradually these were supplemented by retractable or azimuthing and retractable thrusters until fully dynamic positioned drill ships were developed.

The early semisubmersible had no propulsion systems, but thrusters

became practical for propulsion assistance on long ocean transit and for mooring assistance. Thruster units evolved from 600 to 1200 HP fixed orientation propulsion assist units to present day 3000 to 4000 HP azimuthing units designed for dynamic postioning applications.

2.1.8 Mobility

The first generation semisubmersible MODUs featured multiple column and hull arrangements which produced very poor performance while under tow. As the twin-hull semisubmersible evolved, transit condition performance gradually was improved by adopting optimum draft and hull proportions for towing. Bow and stern shapes were selected to minimize wave interaction with the stability columns. Some present semisubmersible MODUs have incorporated ship bows and sterns, including bulbous bows, to obtain high speed in the transit condition with minimum tug assistance.

Jack-up units have also seen improvements in hull shape, including radiused bilges and leg/spud can fairings to reduce towing resistance and motions. When long moves are contemplated for these units, special purpose transport barges are often utilized to carry the jack-up by various dry tow methods. This operational development has reduced considerably the inherent risks of transporting jack-up units over long distances in rough seas.

2.1.9 Stability

In most early MODU designs, stability considerations were limited to provision of sufficient GM and waterplane area to resist the effects of 70 knot to 100 knot storm winds. Gradually other considerations were addressed, and accidental flooding criteria were adopted to enable MODUs to survive damage resulting from boat collisions as well as the effects of severe storm. Classification societies included intact and damage stability requirements in their rules, beginning with the ABS rules for MODUs in 1968.

Present generation MODUs are designed to meet extensive stability requirements which are based on operating experience. MODUs are now designed to withstand a worldwide standard severe storm criterion, plus flooding due to waterline collision damage or other accidental flooding of the hull.

Drill ships and jack-ups are designed to meet one-compartment damage flooding standards, while semisubmersibles are designed to meet one or two-compartment flooding standards for waterline damage and one-compartment flooding for other cases.

2.2 ACCOMPLISHMENTS

In contrasting early and contemporary MODU designs, the following performance capabilities have been achieved:

2.2.1 Payload

First-generation units were designed to carry 500-1000 ST of deck load. Drilling locations eventually extended to remote areas where re-supply considerations dictated large deck load capability. Drill ships had no difficulty in providing deck load capacity in excess of 4,000 ST, but even the largest early semisubmersibles could carry only 1500 ST on the average. Present generation semisubmersibles average 3,000 ST deck load, with some designs capable of carrying 4,000 ST or more at operating draft. This increased capacity enables units to work for longer periods of time which for some units means the ability to drill an entire well without resupply.

2.2.2 Increased Operability

Early ship and barge-shaped MODUs were severely limited in performance if seas exceeded 10-12 ft. Vessel motions and wave forces made it very difficult to work on the units, and mooring equipment could not withstand the wave effects. The introduction of the semisubmersible hull form immediately improved the operability of

the MODU, and most modern semisubmersibles are able to attain a workability of 95% or greater per year.

2.2.3 Deepwater Operations

Early units evolved from Gulf of Mexico practice where water depth seldom exceeded 300 ft and seas were less than 8-10 ft except during hurricanes. Designs were adapted to deeper water in stages, and MODUs can now operate in virtually any water depth, and in seas up to 60 ft without leaving station. Semisubmersibles are now designed to withstand a maximum wave height in excess of 100 ft in some regions, with an associated wind speed greater than 100 knots.

2.2.4 Hostile Environments

Drill ships and semisubmersibles have been used in ice covered areas during ice-free periods of the year. These vessels are ice strengthened at the waterline to protect the hulls against drifting ice. Further advancements are expected in design of ice-classed MODUs, and one unit has now been built for operation in first year level ice in the Beaufort Sea.

2.2.5 Dynamic Positioning

Prior to the introduction of dynamic positioning (DP) systems on MODUs, the maximum water depth for exploration drilling was approximately 1200 ft. With the refinement of DP systems, wells have now been drilled in water depth exceeding 4,600 ft, and waterdepth up to 6000 ft present no technical challenges.

2.2.6 Mobility

Mobilization costs of semisubmersible MODUs have been reduced 50 to 100% by reducing hull form resistance and by increasing the available thruster power. Modern semisubmersible MODUs can transit at 8-9 knots with tug assist and 6-7 knots unassisted versus 6-8 knots and

4-5 knots respectively for the early generation units.

Jack-up units have achieved remarkable improvements in mobilization costs due to the introduction of special purpose transportation barges which allow the MODU to be transported in a dry environment.

2.3 INFLUENCE ON SAFETY

Safety aspects of modern MODUs are discussed in many references included in Section 7. The principal safety features of modern MODUs are discussed in Section 4, and summarized below:

2.3.1 Stability Requirements

Stability regulations now in effect for MODUs exert a large influence on the units configuration and size, and usually limit the payload capacity. The regulations are intended to ensure that a MODU can survive nearly all expected storm conditions and the most likely damage situations without jeopardizing the safety of the personnel on board. The present regulations are designed to limit payload so that the effects of 100 knot winds and waves, or damage flooding resulting from boat collisions do not capsize the unit.

2.3.2 Structural Adequacy

Present design practice incorporates basic design considerations that affect structural adequacy of the MODU and the safety of personnel on the unit. These factors include reasonable factors of safety for design loads, adequate fatigue life, redundant structure or reserve strength, ability to withstand low energy collisions, and appropriate construction materials. In recent years technical advances have enabled engineers to gain a broad base of experience in predicting maximum design loads and a better understanding of fatigue life of structure.

Modern MODUs are designed to withstand collisions with supply vessels

without catastrophic failure of the structure. Vital elements of the structure are often made redundant or are provided with sufficient reserve strength to withstand credible loadings.

2.3.3 Ballasting Systems

Some recent semisubmersible MODU designs incorporate complex ballasting systems capable of correcting the effect of accidental flooding of any tank or even a pump room. These systems may incorporate multiple pump rooms or secondary equipment to afford full operational redundancy.

2.3.4 Emergency Power Supply

Some new MODU designs are including emergency generators capable of operation at large angles of inclination, consistent with damage flooding requirements. This action ensures that the unit will be able to recover from nearly all conditions of accidental flooding.

2.3.5 Inspection and Maintenance

Significant advances in design and construction technology have necessitated similar refinements in inspection and maintenance practices. While these aspects are operational factors rather than design factors, they bear a direct influence on the increased level of safety of modern MODUs. More sophisticated fabrication and testing techniques are employed today to detect and control fabrication flaws or deficiences, and modern MODUs are required by national regulations to attain various levels of fitness in order to be able to operate. Planned maintenance is being implemented on many MODUs as a means of reducing the costs of operation while increasing the unit's operating efficiency.

2.3.6 Lifesaving Appliances

The operators of MODUs have indicated concern with the adequacy of

existing lifeboats and escape capsules. There have been significant advances from the early open boats to the totally enclosed, powered escape capsules, but even more development is needed. The principal objective of industry is the development of a boat or launching system which can be deployed in heavy weather from an inclined vessel. The industry is investigating novel designs for launching systems including free-fall systems, pendulum type capsules, and escape slides. Many systems offer the promise of a breakthrough in personnel evacuation safety, both in the drilling industry and in other maritime industries.

3. GENERAL REVIEW OF MODU DESIGN

3.1 HISTORICAL SUMMARY

A brief history of early offshore drilling is presented to contrast the equipment and procedures used in the beginning with those used by offshore units in operation today. Since the first MODUs appeared in 1950 there has been tremendous growth in offshore drilling. Figure 1 shows the chronological growth of the worldwide MODU fleet from the 1950's to the present. The following sections highlight the technological advances in MODU design over this time period. Design and construction considerations of early MODUs are covered in Reference 1 through 4.

3.1.1 Early Considerations

Three major design considerations governed the introduction and early development of mobile offshore drilling units. The first and most significant consideration was the operating water depth. Since the 1950's drilling progressed from land based operations to increasingly deeper waters. Design for increasing water depths was the single factor most responsible for the development of the different mobile rig types.

A second major factor was the emphasis on design to decrease vessel motions. Early designs were optimized for the environmental characteristics of the Gulf of Mexico which was fairly calm. As offshore drilling moved to deeper waters designs had to be modified radically to operate in more severe environmental areas.

The third major design consideration was vessel mobility. The early days saw posted barges that were difficult to move and limited to water depths of only a few feet. Many regions of the world were considered 'frontier' areas, and the few MODUs in existence had to be relocated over long distances. As the number of fabrication sites worldwide increased, mobility considerations became less significant.

Important major design considerations for each of the rig systems are discussed in greater detail in the systems review Section 4.

3.1.2 Rig Types

Mobile offshore drilling units can be separated into two general groups, bottom-supported and floating. Bottom-supported units include submersibles and jack-up units.

Drillships, drill-barges, and semisubmersible units make up the floating group. These units maintain position at the drilling location either with catenary mooring systems or dynamic positioning.

There are exceptions and overlaps between these broad groups, for example a number of early semisubmersible designs were also capable of operating as submersible units in very shallow water.

The first truly offshore drilling units were inland drill barges which consisted of land rigs mounted on barges that operated in swampy areas with less than 10 ft of water. The drilling equipment was elevated above the water level by installing a raised deck above the barge hull supported by posts. The barge was moved to location and lowered to the bottom and the deck was raised above the waterline. The first generation of mobile units were therefore called "posted barges". The instability encountered when submerging these posted barges required further design refinements leading to the first submersibles.

3.1.3 Submersibles

The first true submersible was the Barnsdall-Hayward design "Breton Rig 20" built in 1949 (Reference 1). This rig featured vertical pontoons which provided stability during the lowering of the barge. Once the barge was seated on bottom the pontoons were flooded and sunk as well in order to minimize the wave forces on the rig.

Several early rigs featured hinged pontoons to provide stability during the lowering stage. However the operators soon recognized that moving parts could not be made reliable in an offshore environment. This limitation led to the development of the "bottle type" submersible, the first of which was "Rig 46" now owned by Transworld Drilling Co. This unit was built in 1956 and had a capability of drilling in 70 ft water depth. "Bottle type" units featured large diameter columns that provided stability for the vessel during towing as well as throughout the lowering procedure.

The success of the "bottle type" design was proven in that it led directly to the development of the semisubmersible type drilling unit. The majority of submersible rigs were limited to water depths under 100 ft. The largest submersible rig "Rig 54" also owned by Transworld Drilling Co. was built in 1962 and could operate in water depths up to 175 ft, which proved to be the economical limit for rigs of this type (Reference 1).

Major configuration considerations included accounting for wave and current forces that tended to scour the seabed around the base of the submersible and possibly move the unit off location. These effects led to development of mud skirts and spuds to provide greater lateral resistance to these forces.

3.1.4 Jack-Up Units

The self-elevating or jack-up type drilling units first appeared in the mid 1950's. They were developed to provide a means of keeping the work platform above the wave crest for depths exceeding the capabilities of submersibles. The "Delong-McDermott No. 1", built in 1954, was the first unit to be used to drill several holes (Reference 1)

Many early MODUs utilized a barge to transport the unit to location. After lowering the legs to the seabed and raising the

deck, the barge was removed. Some types had the barge lowered to the seabed for bottom support after the deck was raised. Excessive leg penetration was a problem with early jack-up designs and this led to the development of spud cans to increase the bearing area of the legs.

Another solution resulted in the development of the mat-supported type jack-up rig. These rigs are characterised by a mat of large bearing surface attached to the bottom of the legs which is used to transfer the loads to the seabed. Mat-type units were particularly well suited for areas with weak soils. The first mat-type unit was the "Mr. Gus II" built in 1957 (Reference 1). A typical jack-up configuration is shown in Figure 2.

One important aspect of the development of the jack-up type unit was the design of the supporting legs and the jacking mechanisms. The first units employed cylindrical steel legs and linear hydraulic grips to raise and lower the hull. As water depth requirements increased, both the jacking system and legs proved inadequate for the increased payloads. This restriction led to the development of the open lattice-type truss work legs and the rack and pinion jacking mechanisms.

Modern jack-up units utilize cylindrical legs with hydraulic-pin type jacking mechanisms for waterdepths up to 250 ft. Beyond this depth the lattice-type leg is used to reduce wave loading which would be developed on large cylindrical legs. Reference 5 covers some of the typical design considerations for jack-up units.

3.1.5 Drillships and Drill Barges

Drillships (self-propelled) and drill-barges (non-self-propelled) developed from coring barge conversions in the early 1950's. The first coring barge was the "Submarex", a 1953 barge conversion with the coring rig cantilevered over one side of the barge. The first successful discovery by a floating unit was drilled from the "D.1", a centerline drill barge that was converted in 1958.

With drilling locations extending to more remote locations and increased water depths, the development of purpose-built drillships appeared in the 1960's. Several designs sought to increase vessel stability, including catamarans and vessels employing outriggers. The use of drillships and barges presented a number of limitations, including poor motions response. These floating units have relatively short heave and roll natural periods and suffer from greater motions when compared to semisubmersibles. Bilge keels and roll supression systems were developed in attempting to minimize vessel motions. The introduction of the turret mooring system, first used aboard the "Discoverer" class drillship in 1964, allowed the vessel to "weathervane" through 360° in order to face the prevailing wind and sea state. Dynamic positioning allowed the same capability of orientation as the turret mooring system, plus the ability to drill in far greater water depths. Figure 3 illustrates a modern drillship configuration. Design and construction of drillships is discussed in detail in References 6 and 7.

3.1.6 Semisubmersibles

Semisubmersibles evolved from the bottom-supported submersible type units as mentioned earlier. The first semisubmersible unit was a 1961 conversion of the submersible unit "Blue Water Rig No. 1". The early semisubmersible units were designed to operate in either the floating or bottom supported mode. A modern semisubmersible design is shown in Figure 3.

The principal design feature of the semisubmersible type is that its major buoyancy members are located well below the waterplane level at operating draft. Because wave particle motion decays exponentially with increasing depth below the water surface, less force is imparted on the buoyant members and the units motions are reduced. Semisubmersibles in general have greatly improved motions characteristics over the traditional ship-shape hull forms of drillships and drill-barges, and these units have evolved as the most common type of unit for operations in deep water.

As with drillships and drill-barges, semisubmersibles can be either self-propelled or non-self-propelled. Self-propelled units have either a series of azimuthing thrusters or a combination of thrusters and traditional shafting and propeller arrangement. The modern twin hulled catamaran type is designed to transit at a shallow draft while supported by the lower hulls. The transit speed of the semisubmersible will never match that of the drillship type due to the high profile and large projected area which results in high wind resistance. Mobility is no longer a significant design factor as modern units spend less than 5 percent of their time in transit between drilling locations. References 8 through 10 discuss the design of semisubmersible.

3.1.7 Well Completion Methods

Two basic types of well control have been used in offshore drilling. The original method was the surface completion method, used in shallow water drilling up to about 150 ft, the limit for bottom supported drilling units. The second method is the subsea completion technique, which was developed to allow drilling to be performed from floating platforms, where vessel motions and wave forces influence the drill string and riser.

In the first method, a conductor pipe is driven into the seabed and extended to the water surface. This conductor supports the above-water blow out preventer (BOP) and well completion equipment. The well head is usually protected by a permanent structure after drilling is completed.

In the subsea completion method, the BOP and well control equipment are installed at the seabed level, necessitating additional guidance systems for installing the BOP, casing and control lines to the surface. A marine riser connects the BOP to the floating drilling unit, and motion-compensating connections are required to permit drilling from the moving vessel.

Virtually all present-day offshore drilling operations utilize subsea completion systems or other advanced techniques, and units must be designed to handle, service, and transport heavy BOPs weighing up to 150 tons.

3.1.8 Dynamic Positioning

Early MODUs could operate conventionally moored in waterdepths up to 600 ft. With improved equipment most MODUs are presently limited to approximately 1500 ft maximum water depth for conventional moored drilling. When water depth exceeds this limit, mooring system components become heavy and the weight of the system detracts from the payload capacity of the unit. In addition, at deeper depths, the positioning capability of catenary mooring systems becomes less effective, and the vessel cannot be maintained over the well in rough weather.

Dynamic positioning systems evolved first as part of thruster-assisted conventional mooring systems. Once control systems were developed to regulate both the thrust and direction of the individual thrusters, full dynamic positioning became feasible. With this development, drilling could be extended to water depths in excess of 1500 ft. An early DP drillship was the SEDCO 445. This unit held several records for deepest well drilled, and it is still in operation.

3.2 SYSTEMS AND FEATURES FUNDAMENTAL TO THE MODU CONCEPT

This section identifies the major systems and features and indicates the nature of their importance. Systems fundamental to the MODU concept are compared with their predecessors as applied to other types of floating vessels (i.e. merchant cargo ships). Concepts developed prior to the mid '70s are based on published articles. Developments beyond the late '70s are based on the authors' expertise and direct involvement in recent designs.

3.2.1 Hull Configuration

The basis for hull form selection and development has been dictated by the following objectives:

- Payload
- Work Area
- Stability
- Motions
- Mobility

References 1 through 4 discuss the early design and selection process. The main considerations in selecting the hull configuration were desired payload, estimated equipment weight, and sufficient stability (compared with traditional ships) to attain reasonable seaworthiness while working.

Whereas the above mentioned factors are all significant in the design of merchant vessels, maximizing mobility for a given payload is the most important consideration. For MODUs the major consideration has been maximizing operability by minimizing motions for a given payload. This led directly to the development of the semisubmersible hull configuration.

There is an important reason for this difference in design objectives. The operations of drilling units differ greatly from those of conventional merchant ships because a drilling unit must remain at a remote location for extended periods of time in order to complete a drilling program. A unit may drill several wells at the same location, each taking 20 - 40 days to complete. A MODU must often withstand more severe weather than ships ever experience. Conventional ships can head for sheltered waters to avoid storms, or can change heading at sea to minimize the effects of a bad storm. MODUs generally don't leave the site unless weather becomes so severe that vessel motions exceed safe drilling conditions. The success of the semisubmersible concept is demonstrated in the North Sea where

modern semisubmersibles rarely are required to shut down due to weather, and year around drilling is common.

3.2.2 Structural Configuration

Structural design practices for early MODUs followed ship rules, or classic ship design principles, but some special checks were carried out to verify the structural requirements in the area of the drilling derrick and substructure.

As new hull types were introduced, more 'engineering' of the structure was required, and structural engineering practice made its way into the offshore drilling industry.

The most challenging design problems for jack-up type units were aimed at achieving adequate leg strength for increasing waterdepth and developing leg-to-hull connections. The jack-up hull was designed as a barge except for provision of adequate strength around the legs. This critical area was designed to support the loads transmitted by the legs and jacking mechanisms. One solution for deeper waters involved the development of tilted or "battered" legs. This presented particular problems at the hull-leg connection in that the angle of tilt varied with water depth when raising and lowering of the legs.

3.2.3 Motions Control

As mentioned above motions control is a driving design factor for MODUs when compared to merchant vessels. Heave motions have an extremely detrimental effect on the drilling capability in that precise control of pressure on the drillbit is necessary for efficient operations. Efforts to minimize heave motions led directly to the development of the semisubmersible hull configuration.

The development of slip joints and heave motion compensators reduced the effect of small vessel motions. However, the advantage of

decreased vessel motions can be seen in the increased operability of semisubmersible when compared to drillships in severe seas.

Lastly the effect of motions control on the crew comfort has not been ignored. MODUs are classified as industrial vessels and when on location their operations are essentially industrial in nature. The general effectiveness, efficiency, and safety on board are all increased with decreases in vessel motions.

3.2.4 Mooring Equipment

MODUs spend the majority of their time fixed at a location. The mooring system must serve two functions, to provide precise control of vessel position above the wellhead and to produce resistance sufficient to hold the vessel on location in a severe storm. These considerations have led to the development of more complex mooring systems than is usually employed for ships. MODU mooring systems involve as many as 12 lines and very large chain and wire rope sizes. Improvements in mooring analyses have led to more confidence in the design and operation of these systems. Anchor types have also been developed for specific offshore applications including wide fluke anchors developed to generate adequate holding power in areas with very weak soils.

3.2.5 Ballast Control

The development of MODU ballast systems was again defined by fundamental differences between the requirements of merchant vessels and those of the different MODU types. For the early submersible rigs, ballast was required only to provide adequate bearing pressure on the sea bottom to resist lateral loads. Jack-ups had ballast pre-load systems, used primarily during the pre-loading of the legs after the unit has arrived on station. Pre-loading involved filling the ballast tanks with sufficient water to ensure adequate penetration of the legs in the sea bottom. For both the submersible and jack-up type units the ballast system was used little, if at all, after arrival and set up on location.

Drillship ballasting was essentially similar to the conventional ship arrangement. The special ballasting requirements for semisubmersible vessels is described in section 4.4.

3.2.6 Stability

Stability considerations of MODUs are no different from those of merchant vessels. The design must provide adequate stability to ensure the safety of life and property. However, as mentioned earlier the MODU has in general less mobility to avoid bad weather than a conventional ship. Advancements in computer analysis techniques and in the understanding of the dynamic effects of sea states on these units is leading to a better understanding of the stability and survivability of MODUs. Specific rules and advancements in analysis techniques are discussed in section 4.6.

3.2.7 Instrumentation and Control

Due to the nature of the industrial operations performed aboard MODUs the instrumentation and control systems are more complex than those used for conventional ships. Advances in computer technology have produced immediate and precise monitoring and control of the vessel systems and increased reliability and redundancy over earlier systems.

3.2.8 Harsh Environment Protection

Throughout the history of MODU development the areas of drilling activity have been extended into increasingly harsh areas. These include operations in colder areas where the problems associated with low temperatures, icing, and the presence of icebergs have led to design changes. Early designs adapted for cold weather featured weather barriers around the drill floor and set back areas, and winterized equipment. The most recent designs have considered cold weather climatization as a systems problem, and have incorporated

hull heating systems, de-icing systems and fully enclosed drilling areas. These improvements are meant to increase or maintain the level of safety for MODUs operating in these areas.

4. SYSTEMS REVIEW

The following sections identify trends in design of of the more important MODU systems. Where possible an effort has been made to point out major differences in the various systems when they depend on rig type.

4.1 STRUCTURE

Review of structural design considerations has been limited to three main factors: configuration, welding techniques, and materials. These aspects are presented in detail below.

4.1.1 General Considerations

The evolution of the primary structure of jackups, drillships, and semisubmersibles parallels the systematic exploration for oil and gas in deeper water and more severe environment.

In most cases, the structural configuration is governed by the operational or naval architectural requirements associated with drilling in deeper water while minimizing downtime. From a structural standpoint, operational requirements include maximum variable load (VL) and minimum downtime. Naval Architectural requirements include minimizing motions and maximizing transit speed while meeting intact and damage stability requirements. Secondary factors which affect the detailed structural arrangements are construction and maintainence costs, fabrication methods, and redundancy.

Fabrication cost factors dictate simple structural systems, with the minimum number of members and joints. Fabrication methods are primarily dependent on the contractors' equipment and capabilities. Highly redundant structures provide low static and cyclic stresses which improve fatigue life and overall safety, but increases the number of members and joints in the structure.

4.1.2 Jack-up Configuration

There are several unique structural problems to consider in the design of jack-ups; the upper hull, leg-to-hull connections, leg-to-mat connections, and the legs themselves.

The upper hull is designed and constructed as a barge. The hull is also checked for the imposed concentrated loads due to the drilling structure. Although the upper hulls in modern jack-ups are larger and the drilling structures more extensive than in past units the basic design and construction practices for these systems are the same as for early units.

As jack-up variable loads, operating depths, and design environments increase, the leg and connection design and construction become increasingly complicated. The interaction of jacking system and leg-to-hull connections, dynamic amplification, secondary moments due to side sway, and low cycle fatigue during transit must all be considered in the design of these components.

Except for larger components, the basic configuration of jack-ups has remained the same. New fabrication techniques have been introduced, such as using cast leg nodes, but the number of legs and upper hull compartmentation have remained the same.

4.1.3 Drillship Configuration

Many of the early drillships were conversions of existing ships and the basic structural design of the vessel was governed by existing standards and rules for ships. The conversions were engineered to withstand the additional loads imposed by the drilling equipment and the maintenance of longitudinal strength in the way of centerline moonpool.

Design variables have relatively little impact on the primary structure of the drillship, other than increasing the size of the drillship for increased variable load or providing ice strengthening for operations in specific areas.

Purpose-built drillships follow standard design and construction guidelines and their performance record to date indicates no reason to deviate from present practice.

The following procedures and features characterize present construction practices:

- Straight sections with stringer stiffening
- Square bulkhead intersections
- Full penetration joints primarily at plate seams
- High structural redundancy provides low static and cyclic stresses

4.1.4 Semisubmersible Configuration

The first semisubmersible units were conversions of the "bottle type" submersible designs. These units incorporated modification of the mooring system and conversion to a subsea BOP system. No major structural modifications were required.

One of first purpose built semisubmersible designs was the SEDCO 135 series, a triangular configuration with three separate stability columns. At the base of each column was a large footing providing buoyancy as well as storage compartments for ballast, drillwater, and fuel oil. This design could be used as a submersible for sitting on bottom in shallow water or as a semisubmersible in deeper water. One design objective of this type unit was to avoid the assymmetry of the earlier conversions where the drilling package was located away from

the primary structural system. This new design attempted to place the drilling equipment closer to the center of buoyancy of the unit to provide better motions at the drill area and provide a simplified structural framing arrangement.

The triangular units represent the most efficient structural system possible for an offshore drilling unit, however, they have little structural redundancy.

The desire for increased transit speed and mobility led to the development of the modern twin-hulled semisubmersible unit. These units had similar or improved deck load and motions characteristics to the triangular units, with greater transit speed. In addition structural redundancy was enhanced in these design types.

Three primary configurations of the twin-hulled type units have been built:

1. Stability columns with a platform deck framed with vertical tubular trusses. The SEDCO 700 series is an example of this type of unit.

2. Stability columns with a barge or 'box' deck framed with vertical tubular trusses. The Bingo 3000 is an example of this type of unit.

3. Stability columns with barge deck without vertical trusses. The GVA 4000 is an example of this type of unit.

The platform deck is easier to build, and provides maximum flexibility for future modifications or additions to the drilling unit. The barge deck, while more complex and less easily modified, provides some reserve buoyancy.

Vertical trusses allow multiple support points for the deck structure and provide a lighter deck and simpler deck to column connections. Vessels without vertical trusses have fewer braces and nodal points.

Basically, all three configurations have positive and negative aspects. However, unless Regulatory bodies require reserve buoyancy in the deck, all three configurations will continued to be used in semisubmersibles.

4.2 MATERIAL AND WELDING

4.2.1 Materials

The various grades of ship steels are typically specified in the design and construction of MODUs. These steels are specified by the classification societies (CS) in the various MODU rules and are familiar to all potential fabricators of these vessels. Previous experience with these steels in ocean going vessels provided relevant guidance in the selection of steels for hulls, mats, deck and other similar structures. However, at locations such as braces, columns, legs and main structural girders, and especially at intersections of these members, there was no direct shipbuilding precedent. Moreover, a trend towards higher strength steels was evident by the mid 1960s when the AH/DH/EH steels were included in the CS rules (Ref. 11). Thus, by the early 1970s the need for a comprehensive set of guidelines for steel selection for MODUs was being addressed by CSs worldwide.

A system for the application of the various steel quality grades was developed by DnV in the early 1970s for fixed platforms, as discussed by Wintermark (Ref 12). This system divided structural applications into special, primary and secondary structure. These application categories were similarly adapted to MODUs by ABS as reviewed by Alia et al(Ref. 13) and were incorporated into the 1973 ABS MODU rules. Similar considerations were given in the Lloyds (1975) and DnV (1975) MODU rules except Lloyds formally recognized only two categories (primary and secondary) and specific categories were not formalized in the DnV rules.

Material selection and non-destructive testing techniques are described in References 13 and 14. The temperature shift/NDT approach is still the most practical approach for the selection of steels. It affords relatively inexpensive quality control testing using the widely accepted charpy V-notch (CVN) test on a per plate or per lot basis. The CVN acceptance criteria is correlated to the structural application by choosing a CVN test temperature relative to the minimum service temperature. For example, the 1980 ABS MODU Rules under Section B.9, "Other Steels", requires CVN testing 30°C below, 10°C below and at the minimum service temperature for special, primary and secondary steels, respectively. Extensive service experience with the ship steels has shown however that some relaxation from this criteria can be justified based on the additional ductility inherent in thinner (plane stress) sections of these steels. Thus, the application of classification society steels for thinner sections may be somewhat relaxed over the rigorous temperature shift criteria. For example, compare Table B.1 and Section B.9 of the 1980 ABS MODU Rules.

Typical bracing trusses between columns or caissons of semi-submersibles are comprised of relatively heavy wall tubulars with diameters ranging between 3 and 9 ft, but commonly in the 4 to 6 ft range. Connections between these members are often direct tubular to tubular joints at various intersection angles are made with full penetration welds, although crotch plates are sometimes used. Such joints can have welds up to twice the adjoining member thickness and produce considerable contraction strains especially in the through member. Thus, lamellar tearing (LT) has been of considerable concern. This problem is exacerbated by the relatively heavy wall thickness members encountered on these rigs. Early experience led to specifications for the ultrasonic examination (UT) of plate steel (e.g., ASTM A435) to enable rejection of plate which contained gross laminations and/or non-metallic inclusions.

This procedure served to identify only the most susceptible material, and the through-thickness tensile test, introduced into the 1975 DnV

MODU rules, was required to adequately control the problem. The occurrence of LT can now be eliminated by the use of modern 'clean' steelmaking processes with desulfication, inclusion shape control and the UT and through thickness tests noted above.

While engineered fracture control plans coupled with experience in ship fractures, beginning with the Liberty Ships in World War II, have provided the basis for steel selection rules, practical considerations have also played a part in the development of individual owner requirements which may not be specified by Code. The problems of heavy wall tubular construction surfaced in the construction of fixed offshore structures, although similar problems are encountered in MODUs. In addition to LT, as discussed above, the forming and welding of these members required further consideration with respect to degradation of properties during heavy forming and to the problem of hydrogen cracking. However, in locations of structural significance, the use of the required higher quality steels has been found to minimize these considerations since severe (greater than about 4%) forming strains are not typically encountered on MODUs and the hardenability of the steels are limited by the specification. In addition, classification societies have generally limited the use of welding consumables with higher hydrogen potential to low strength steels, as discussed in the next section.

Another area where significant development of materials has occurred is in the legs and jacking rack gears of jackup type MODUs. Early experiences with cracking at leg-to-mat/spud can and lattice tubular end connections led to changes in materials and especially in design to compensate for the heavy cyclic loading encountered. However, the use of high strength materials for the legs and associated jacking structure was extremely important since the weight of the legs must be offset by hull/mat buoyancy. Thus, steels up to 100 ksi yield strength are common in racking gears typically 5 inches thick. Early designs used steels such as 8630 and other hardenable grades borrowing from the metallurgy of gears in mechanical design. Welding these steels required high preheat/interpass temperatures, some form

of postheat and/or slow cooling and extremely careful conrol of welding consumables to avoid cracking. High strength low alloy steels such as the ASTM A514/A517 grades have since been used to take advantage of the greatly improved weldability, minimal preheat and postheat requirements and good notch toughness these newer steels provide.

Advances in steel making are continually upgrading the fabricability of steel although not all MODUs require such technology. One area of concern to both owner and fabricator is the requirement of weld heat affected zone (HAZ) toughness properties, since the more efficient higher deposition rate welding processes tend to reduce weldment toughness, especially in the HAZ. One method of control is to set arbitrary limits on the welding heat input. However, the recently built ice breaking drilling unit, KULLUK, which was designed to a minus 50 degrees celsius minimum service temperature for Canadian artic waters, used state of the art steel which enabled extremely high welding heat inputs to be used without significant reduction in HAZ notch toughness, as verified by procedure qualification testing at minus 60°C.

4.2.2 Welding

MODUs are typically fabricated at a shipyard site. While extensive facilities are not required for the construction of jackups or barges, the basic fabrication methods are similar to modern well equipped shipyards except for scale. Regardless of the site, most structural fabrication is on the critical path since an early launch is desired to clear valuable slipway or drydock space for the next vessel and to facilitate outfitting alongside the quay. High production welding rates are assumed in schedule planning to meet these deadlines. Quality control in shipbuilding relies primarily on the Classification Society surveyor system wherein the certification required by the owner is contingent on the completion of all work to the satisfaction of the CS surveyor. This system of welding,

fabrication and outfitting quality control has not changed significantly over the course of MODU history, although it has increased in scope and is now more commonly supplemented by additional owner surveillance.

Ship structures are comprised primarily of plating joined by butt welds and stiffened by fillet welded bulbs, angles, tees or other shapes. Corresponding structure in semisubmersible units are hulls (pontoons, caissons, etc.), large diameter columns and some deck structures. Bottom mats, upper hulls and cylindrical legs of jack-up units are designed, and fabricated in a similar manner. Fully automatic submerged arc welding (SAW) remains the primary method of making butt welds. In the modern shipyard, SAW is coupled with positioners, material handling devices and other equipment to provide a near assembly line process flow wherever possible. In some installations full penetration welds are made from one side by the use of backing trays with flux which are placed up against the weld joint by mechanical lifters, eliminating the need for turning plates, back-gouging or overhead welding. Alternative methods have been qualified using ceramic or other backing, sometimes also using flux. Multiple wire (electrode) SAW is now common since adequate properties can be achieved at highly favorable production rates.

Although shielded metal arc (SMA) welding (also called manual metal arc (MMA), or stick welding) is still used for making fillet welds, this process is being replaced by others. Gravity welding is used extensively especially in the Far East where numerous grades of the long (28 in.) electrodes are available. Semi-automatic welding processes, such as the gas metal arc (GMA), fluxcored (FCA) and semi-automatic submerged arc (SA) welding processes are also replacing the SMA process, even in awkward locations where gravity welding is not possible. The application of self-shielded FCAW has greatly increased owing to its ease of use, its ability to be used outdoors and its good deposition efficiency.

The primary method of control in the selection of welding procedures for MODU fabrication is through the use of approved consumables lists developed and maintained by the classification societies. This system was developed in the late 1960s and early 1970s out of the need to control welding considering the large multiplicity of weld consumables. In this scheme, the approval given is tied directly to the ship steel grade. Thus, weld metal properties (e.g. strength and toughness) and consumable types (e.g. low hydrogen) are compatible with the choice of material given in the design.

4.2.3 Fatigue Considerations

Advances in the understanding and analysis of fatigue led to changes in welding procedures for semisubmersible fabrication. For example fillet and partial penetration welds were eliminated in fatigue sensitive areas. This step took some effort since these details are acceptable virtually anywhere on a ship and were previously applied in "non-structural" welds to structural members. An example of the misapplication of this detail was the hydrophone attachment weld on brace D6 of the Alexander Kielland (Ref. 15). Often these details provide fully satisfactory service, although under severe environmental conditions, such as found in the North Sea and North Atlantic, full penetration welds are necessary.

In general, welding for MODU fabrication has not evolved significantly faster than other heavy fabrication industries in the same geographic region. Experiences in offshore fixed platform tubular structures have significantly advanced the state of the art in the ultrasonic examination of tubular intersection joints and in other aspects of the fabrication of these configurations. Similarly, weld stress relief is considered at thicknesses above 2 to 2½ inches in keeping with shipbuilding and U.S. Gulf Coast platform experience. However, these practices have remained essentially intact since advances in materials and inspection procedures have generally kept up with changes in requirements.

4.3 MOTIONS CONTROL

4.3.1 Background

In the early years of the offshore industry, virtually all drilling was done from bottom supported platforms. Motions were not a consideration except for transportation and no special provisions were made. Designers did, however, strive to reduce wave forces imparted to the platforms. Methods developed to achieve this objective found application later on with floating platforms to minimize wave induced motions. The shape and size of the hulls were controlled by considerations of resistance to current, speed under way, and stability.

4.3.2 Drillships

Little can be done with a ship-shape drill vessel to reduce heave and pitch motions since the exciting forces are so large. The problem of roll motion reduction is the same as for any ship and several systems are available for this purpose. These include bilge keels, tuned tanks and gyroscopic stabilizers.

Bilge keels are almost universally used for drillships and other ships and are effective in reducing roll but more while underway than when moored.

Tuned tanks, which operate on similar principles to those used for reducing heave on a semisubmersible, have been used on several drillships. While they do consume space and weight, they are often cost effective for a drillship, which when moored is not able to head into the waves to reduce roll. Even for a dynamically positioned vessel they can be used to advantage since the optimum heading may not be head-on to the waves. Lastly, waves may approach from more than one direction and roll damping tanks will be able to cut down on motions induced by the non-head seas.

4.3.3 Semisubmersibles

The most significant and successful hull configuration to achieve motion reduction is the semisubmersible. This first appeared in 1961, when the "Blue Water No. 1" was converted from a submersible, or sit-on-bottom unit.

The low motions of the semisubmersible derive from the location of the large buoyant members well below the free surface. Members at the surface are only large enough to achieve adequate stability. As mentioned, the same principles were used earlier to reduce wave forces on bottom founded units.

Of the six degrees of freedom (heave, pitch, roll, surge, sway, yaw) it is heave which is most troublesome for drilling operations. The semisubmersible configuration has very low heave motion for the reason already mentioned. One manifestation of this behavior is the length of the natural heave period, which is typically greater than 20 seconds for a medium or large unit. Since wave periods greater than 18 seconds are rare, the platform is effectively detuned with regard to heave. The same is true for roll and pitch. Figure 5 shows a comparison of heave motions for a drillship and a semisubmersible.

While all semisubmersibles derive their good motion response from these principles, the resultant configurations have varied widely. Units with anywhere from three to fourteen primary stability columns have been built. Submerged buoyancy members have varied in number, size, orientation and shape. Recent trends are toward reduced numbers of columns, buoyancy members and braces. Most recent designs incorporate two longitudinal pontoons for primary buoyancy and four, six or eight stability columns, with a small number of brace members. This configuration offers a good combination of speed, motion response, and structural reliability.

Some things can and have been done to further reduce motions of a semisubmersible. When the drill derrick is placed off center, the hull and column arrangement can also be made asymmetric to provide lower motions at the end where drilling is done.

On a symmetric design, the wave forces acting on columns and pontoons can be balanced to minimize heave exciting forces, at least for the range of predominant wave periods. However, since this results in pontoons which extend far beyond the outermost columns, some compromise must be reached to avoid interference with the anchor lines.

Special tanks can be incorporated to reduce heave and/or pitch and roll forces. These may communicate with the sea or may be a closed system. These tanks provide inertial and viscous forces in opposition to the wave forces. Such tanks find more application in smaller semisubmersibles where the heave natural period may be too short to prevent resonance with long waves.

4.3.4 Jack-ups

Motion reduction is not a question for jack-up units except while being moved and while jacking up or down. Delays of days or weeks can occur waiting for moderate weather to jack down or up on location. While under way, motions determine the length of leg which can be safely carried.

Until recently there has been no specific attempt to moderate these problems with motion reduction systems. Some units now incorporate tuned tanks on the periphery of the unit which are effective in reducing roll and pitch. These are included either in the original design or as a retrofit item. Roll damping tanks consume weight and space, but are cost effective for a jack-up operating in other than a mild weather area.

4.4 MOORING SYSTEMS

4.4.1 Background

The size and weight of mooring systems have increased as a function of the design water depth. Sometimes the systems are too heavy to be carried aboard the drilling unit and are transported and set in place by support vessels. A modern mooring system for deep water can weigh 3000 tons or more. Mooring is possible in depths to 2500 ft depending on the environment.

A modern world-wide drilling unit does carry its own mooring system on board and deploys or retrieves anchors with assistance from anchor handling boats. If a unit is capable of dynamic positioning, it may or may not have a conventional mooring system in addition. While there is enough confidence in DP systems now to dispense with anchors as a backup, it is not economical to use DP in moderate depths, and not possible to do so in very shallow water.

4.4.2 System Components

A typical mooring system consists of 8 to 12 anchor lines of chain or wire rope or a combination, up to 6000 ft in length per line. Chain or wire rope sizes range between 2 and 3-½ inches. Chain performs better in deep water due its weight, which provides a horizontal force at the anchor to prevent uplift. Wire rope is better in shallow water due to its greater elasticity which minimizes tension peaks from vessel motion. Some units have combination systems to capitalize on the advantages of each system.

While chain is heavier than rope, it is usually carried lower in the unit such that the weight disadvantage is minimized. Some modern units have winches or windlasses located inside the columns or pontoons instead of on deck to improve stability.

Anchors for drilling units must have high holding power and must be easy to rack. Each anchor can weigh up to 45,000 lbs. Anchor types in use include Danforth, LWT, Bruce, Delta Flipper and variations. In poor holding ground, more than one anchor per line may be necessary, called "piggybacking." Sometimes anchor piles are driven if holding power is very poor.

4.4.3 System Selection

Sizing of mooring systems is done using both experience and analysis. The state of the art in predicting vessel motions and anchor line dynamics are not by any means exact. This has led to difficulties in analytical predictions of line tensions. Empirical methods are used to evaluate a mooring system for a given depth and environment, with general success. On board computers are making it possible for operating personnel to carry out these evaluations, to optimize the anchor pattern, and to predict tensions.

Shipshape drilling units have much higher forces when the weather is on the beam instead of ahead. The introduction of turret mooring systems which allow the vessel to rotate in response to the environment have minimized this problem.

Recent developments in mooring systems include very high strength chain, emergency quick disconnects, automatic tension monitoring and load sharing, and replacement of anchor buoys and pennants with chain chaser lines.

4.5 BALLASTING

Early MODUs and especially jackups, did not have dedicated ballast systems until the introduction of submersibles and semisubmersibles. At best, most units had some type of bilge pump/draining arrangement, as provided by classification society rules.

4.5.1 Bilge/Drain Arrangement

The bilge/drain systems have been utilized on mobile offshore drilling units in one form or another since their inception. These bilge systems assured dry void tank and pump room spaces below deck. Other spaces such as ballast, fuel oil, and drill water tanks were serviced by separate pumping system. In early designs the bilge system was minimal. A single small pump was used in each of the pump rooms, operated by a float switch, with a high water alarm in the event water reached a predetermined level. The watertight spaces below the pump room were serviced by ballast pumps. These earlier units were intended to operate in relatively calm waters with "sit-on-bottom" capability which could require a considerable amount of ballast. Later designs added a second pump in each pump room.

Modern twin-hulled semisubmersible drilling units have pump rooms installed in both hulls. Many spaces in the columns are classed as voids and a large bilge network is required. A typical bilge system consists of a bilge hat with strainer, stopcheck valve (or gate and check valve), branch line, bilge manifold, strainer, bilge pump and overboard discharge line. Design of the bilge systems follows ship classification rules and a large number of reach rod operated valves are required. Some contractors bilge their chain lockers by draining them into a column void and then into the bilge main. However, operational problems with mud have led some operators to incorporate two drain lines, one to the bilge for relatively clean water and one overboard for the heavier muds. This overboard discharge can only be used in the light draft condition. Other contractors use eductor systems to bilge their chain lockers.

The bilge systems were quite simple on the earlier mobile drilling units. They have become more complex with the use of more void spaces. Recent regulatory changes have increased subdivision requirements, the increase in void spaces will result in more complex bilge systems. The method of valve control may change in response to these events.

4.5.2 Ballast Capacity and Arrangement

MODU ballast system arrangement and function differs from that of conventional ships. For jack-up units several approaches are used to trim the unit while afloat. Upon arrival on location, and after the hull is jacked up out of the water, independent leg jackups must use a pre-load system. This system is similar to a ballast system except that its sole function is to transfer sufficient weight to the legs to ensure proper penetration in the sea bed. After the required penetration is achieved the tanks are deballasted and no further ballasting is done. For mat type jack-ups the mat must be filled with water to provide the necessary bearing pressure when on location. Prior to a move however the mat must be de-watered by use of air pressure to force the water out of the mat.

Floating type units require more continual use of the ballast systems in order to maintain proper trim of the vessel when on location. Due to the constant shifting and application of loads (shifting or addition of supplies, hook loads, etc.) the ballast system is used continuously. For drillships, weight compensation is not as important as for semisubmersibles, and the ballast arrangement is similar to that used for conventional ship structures. Semisubmersibles are of significantly different configuration however, and the development of their ballast requirements is discussed in detail below.

Ballasting of early units was accomplished by gravity flooding into the bottom tanks, deballasting required pumping a bottom ballast tank empty. If tanks above were to be deballasted or ballasted they were connected to a central tank which communicated with a bottom ballast tank. Although operators could control such systems safely, there was a general desire to have a somewhat more positive and direct control of each ballast tank. This desire resulted in the centralized ballast manifold which allowed valves to be more accessible and each tank can now be controlled individually. The

only disadvantage of this new arrangement is its decreased operability at large angles of trim.

Some of the earlier units had several shortcomings in the ballast arrangement. The submerged valves were inaccessible, these valves relied on spring pressure to close and the only way to ballast or deballast some tanks was to open them to another tank. The development of ballast arrangements has been towards more centralized and accessible equipment.

Operational problems convinced some owners that there was a need to prevent transfer of ballast from a forward tank to an aft tank (or vice versa) when both tanks were opened to the ballast manifold. Such a movement of ballast would cause loss of trim resulting in more ballast transfer. Isolating the forward tanks from the aft tanks with a manually operated valve in the manifold prevents any such transfer even upon malfunction of other valve operators. These isolation valves have been installed in many units.

With units being required to sustain more severe damage conditions, the number of tanks will increase. With the increasing complexity of systems the trend will be to more sophisticated control systems. If safety is to be increased or at least maintained design for reliability and simplicity in these systems must be encouraged.

An additional safety feature used by some operators is the secondary deballast system. This provides a redundant system separate from the primary ballast system which is powered by the emergency generator and can empty ballast tanks in the event of damage or excessive heel in a vessel. If damage should occur at a light draft then counterballasting would be the safest measure to pursue.

4.5.3 Pump Room Arrangement

The pump room provides for the pumps, valves, and controls which pump the sea water, ballast, fuel oil and drill water. These functions maintain vessel trim and heel, cool the engines, and provide needed supplies such as fuel oil and drill water. Early designs had a pump room at the top of each column. Although pump room access was quite easy, the pump and valve servicing was not. In some designs pumps and submerged valves were a constant source of maintenance problems. The modern twin-hulled design, with its lower hull pump rooms, provides easy access to valves, pumps and controls. The pump room access is somewhat more difficult on this design, however, elevators simplify matters considerably.

4.5.4 Pump Controls

Ballasting operations are generally controlled from a top-side control room. Details vary depending on the type of valve operator employed, but pump and valve controls are usually hard-wired to a mimic panel in the control room. Local control of all valves and pumps from the pump room can also be provided.

Recent units employing a distributed, multiplexed monitoring and control system (see Paragraph 4.7) do not have hard-wired controls or a ballasting mimic panel. Instead, the system computer generates a ballasting graphic display on the CRT similar to the mimic panel. Valves and pumps are controlled by issuing commands via the keyboard.

4.6 SHIPS SERVICE SYSTEMS

4.6.1 Fire Protection

Methods of fire protection employed onboard rigs consist of active systems like fire hoses, fire extinguishers, and fixed fire extinguishing systems and passive measures like fire barrier

bulkheads using fire resistant construction materials. Fire resistant materials are used in rig construction to reduce the likelihood of a fire and to minimize the amount of combustible material (fuel) available to a fire should one break out.

Many of the bulkheads and decks are designed and built to stop or at least slow the spread of a fire. Much of the design and construction effort in installing bulkheads and decks that are effective fire barriers is in maintaining the firetight integrity around cable, pipe, and ducting penetrations and also around doors and hatches.

Fixed fire extinguishing systems, foam, Halon or CO_2 are also frequently installed. Early units usually had fixed fire extinguishing systems in only the boiler room and paint locker. Today these systems are provided in all areas or compartments having fire hazards including the boiler room, engine room, fuel oil service areas, paint locker, and helicopter deck and fueling facilities. In general Halon or CO_2 smothering type fire extinguishing systems are used in enclosed spaces and foam systems are used in open areas like the helicopter deck.

Recently Halon has been used in favor of CO_2 systems. Halon systems are smaller, more compact and lighter than an equivalent CO_2 system. However, the most important feature of Halon is its reduced hazards to personnel. CO_2 systems work on the principle of displacing the oxygen available to the fire. If personnel are in the compartment when the CO_2 is released their chances for survival are slim as their oxygen supply is also lost. Halon on the other hand works on the principle of chemically inhibiting the process of combustion. Personnel caught in a compartment when Halon is released have a much greater chance of survival.

In the future the fire protection and fire control systems are expected to continue to increase in scope, complexity and redundancy. Designers aim to reduce the threat to safety of personnel and equipment due to fire.

4.6.2 Mechanical Services

The size and complexity of mechanical services have increased with the size and complexity of MODUs. Larger generator engines have required more cooling water and more fuel oil. Centrifuges have been added to fuel oil (and in some cases, lube oil) systems to provide cleaner fluids. Hull storage of brine has been added to make certain types of drilling more economical. Compressed air requirements have increased and the more economical rotary screw machines have replaced reciprocating compressors. Both liquid and dry mud systems have been increased to provide for more equipment and larger flow rates. Some of the most recent drilling units are reversing this trend with smaller units requiring fewer services. These units are generally suitable for less severe weather and seas.

4.6.3 Electrical Power Generation and Distribution

Drilling units require both AC and DC power. DC power is required by the DC drilling motors with AC power supplying all other system needs. Early units generally used a combination of AC generators operating at 480 volts and DC generators operating at 750 volts.

Today most MODUs generate their DC power by converting AC power to DC though SCR systems (silicon-controlled rectifiers), thus eliminating the need for separate DC generators.

Early units had very limited propulsion systems (or none at all), and consequently power requirements were modest (2000 KW was a typical rig load). Power was usually generated at 480 volts. Today, large self-propelled units have greatly increased power requirements. A dynamically-positioned unit may have an 18,000 KW (24,000 HP) generating capacity. For efficiency this requires generation and distribution at a higher voltage, usually 4160 volts.

The power systems on small units, such as jack-ups have changed little (with the exception of the addition of the SCR system) and still generate power at 480 or 600 volts.

The advent of dynamically positioned MODUs placed new demands on the power system in terms of reliability. On an anchored vessel, loss of power is usually only an inconvenience; on a DP unit it is more serious due to the possibility of drifting off station. Thus, power systems for DP units must be carefully designed with adequate redundancy to assure continuity of power.

4.6.4 Control Rooms

Monitoring and control of vessel service functions such as ballasting, fire and gas detection, and interior communications are typically controlled from a central location. On units with propulsion systems, this control room is usually part of the wheel house.

Monitoring and control of drilling functions is primarily done from the drill floor, but backups for critical systems, such as BOP control, are often located in the Toolpushers Office providing redundancy for these critical systems.

Advances in control, detection, and computer technology have allowed increasing use of remote control and monitoring systems. This has served to increase the general level of safety on board MODUs through added redundancy for control of critical systems.

4.6.5 Propulsion

Propulsion systems vary in size from none to 25,000 hp. Jack-up units are towed from location to location and have no need for propulsion systems. Semisubmersibles and drill ships are generally self-propelled and will have propulsion systems on the order of 6,000 to 10,000 hp for use in transit and to assist in mooring.

Dynamically positioned units have the greatest propulsion requirements, as much as 25,000 hp. These systems are designed to keep the unit stationary in the most severe sea conditions without assistance from a conventional mooring system.

Propulsion systems are usually diesel-electric. The main engines drive generators which in turn supply electric propulsion motors. Depending on the type of unit, the propulsion may be conventional in-line propellers, fixed thrusters, azimuthing thrusters, or any combination of the three.

4.6.6 Lifesaving Appliances

The lifesaving appliances supplied on board most units comprise lifeboats, life rafts, lifebuoys, life jackets, fireman's outfits, distress signals, stretchers and other life protecting devices. There has been a general trend among regulators to increase the number and type of lifesaving appliances on drilling units. The greatest area of change has been in design of the lifeboat. The steel lifeboats of the 1950's were replaced by fiberglass boats in the early 1960's. This change was initiated by cost and life expectancy concerns. Later improvements included the use of enclosed lifeboats in the early 1960's which were based on earlier tanker usage. Many of these early craft were conventional open boats. The Brucker capsule, a totally enclosed lifeboat, emerged about 1965. Totally enclosed survival craft emerged around 1971 and operations in the North Sea resulted in requirements for a self righting craft. Fire protection of these craft has also been added to provide for safe passage through burning oil.

The latest developments have been aimed at the problems of safely launching a survival craft during storm and damage conditions. Three concepts have emerged: 1) a water entry system using a hydraulic decelerator on the boats bottom to lessen the impact of a free falling boat, 2) a free fall lifeboat which gets the craft quickly into the water and away from a damaged unit, 3) a progressive

outboard deployment scheme which uses a mechanical means of getting the craft into the water and away from the unit. This last scheme utilizes a fiberglass pole extended away from the unit, this pole flexes and imparts velocity to the craft away from the unit as it enters the water.

The basic developments have come from the vendors supplying lifeboat equipment with the regulatory bodies requiring those functions which enhance safety. Future progress in this area will seek a balance between additional regulations which enhance safety and over regulation which reduces initiative and new design development.

4.7 STABILITY AND WATERTIGHT INTEGRITY

4.7.1 Intact Stability

The first mobile offshore drilling units were the submersible barges which derived from the posted barges. The latter were used in bayou and swamp country with water depths generally less than 20 feet. The early units suffered a major stability problem when going to increased depths. This difficulty was the interval of negative stability when the barge submerged and descended to the bottom.

The elementary requirement of remaining upright during this operation was provided for in a number of ways. These include multipart barges with hinged or sliding sections, non vertical descent winching systems, and multiple stacked barges.

The solution which has endured for submersible units is to provide bottle type deck supports instead of posts. These provide a controlled descent with positive stability throughout. The other methods involving moving parts were found troublesome and vulnerable to damage when afloat and moving. This configuration for submersible units carried over to the semisubmersibles. The first example was the "Blue Water No. 1" which was in fact a conversion of a "bottle type" submersible.

For intact stability the primary requirement remained that of maintaining positive stability (positive metacentric height or GM) at all drafts and sufficient GM at operating draft to facilitate the drilling operation itself. For units with the drilling derrick off center, this could be a serious problem due to trim induced by large variable drilling loads on the hook and derrick.

Designers were left to their own devices in deciding what amount of intact stability was sufficient. Various criteria were employed. Aside from considerations already mentioned, they were borrowed from ship design practice including examination of righting arm curves and provision of adequate freeboard. For semisubmersibles there was no particular problem or deficiency in intact stability once the requirements for drilling and changing draft were met.

Much the same situation existed for jack-ups and shipshape units. For these the freeboard is an important parameter influencing the intact stability. International load line regulations provided satisfactory guidelines for ships. For jackups, the casualty record under tow is not as good as for ships and semisubmersibles. This can be attributed in part to a less seaworthy hull form including the amount of freeboard. Another major cause of accidents in jack-up type units involves the critical stage of transition from a floating vessel to a bottom supported one with the hull raised above the sea level. As the legs set on the bottom and begin to support and lift the hull out of the water a sudden loss of soil support could lead to excessive penetration by one or more of the legs. This could lead to mechanical or structural failures and in the worst case capsizing of the vessel.

The first formally published rules for intact stability of MODUs appeared in 1968 (Reference 16). These rules were formulated by representatives of the offshore industry and issued by the American Bureau of Shipping. The basis for intact stability was the now familiar "1.4 rule" which has since become the "1.3 rule" when applied to semisubmersibles.

Prior to this, the U.S. Coast Guard had applied similar rules to ships and semisubmersibles dating back to 1964. In 1966, the 1.4 rule appeared in internal policy documents.

The rule has it roots in U.S. Navy policy for ships. Explanations can be made with reference to Fig. 6 showing a typical plot of righting moment and wind heeling moments. Areas under the curves are designated by letters A,B,C,D, past and present Navy criteria include the following:

1. $A \geq 1.75\ c$
2. $A \geq 0.4\ (A+B)$
3. $A \geq 1.4\ (C+D)$

The current rule is

4. $A+B \geq 1.4\ (B+C)$ for ships, jackups
   $A+B \geq 1.3\ (B+C)$ for semisubmersibles

All these rules are attempts to account for dynamic effects of wind and waves in a seaway. The procedure of using the static righting and heeling moments for this purpose is not more than an empirical rule of thumb and cannot serve as a consistent measure of stability for different marine structures. In addition the guidelines for determining the wind heeling moment are vague, this has led to differences in application of the rules by different designers.

There has always been a desire for more rational intact stability criteria, but this remains an elusive target due to our incomplete understanding of the environment and its effect. Following the Ocean Ranger disaster there has been increased attention directed to the problem including the following aspects.

1. Wind dynamics
2. True wind drag and lift

3. First and second order wave effects
4. Vortex effects
5. Wave-current interaction
6. Mooring system effects

Thorough research of all these topics may take many years. However present knowledge allows us to step beyond the empirical rules now in use. The present focus is to do so; to improve upon the rules now in use, while at the same time pursuing better understanding of the problem. Agencies involved in this effort include the American Bureau of Shipping, and Society of Naval Architects and Marine Engineers, the International Association of Drilling Contractors, the International Maritime Organization, the Norwegian Maritime Directorate, the UK Department of Energy and others.

4.7.2 Damaged Stability

The term damaged stability refers to inadvertant flooding of one or more compartments within the vessel by whatever means. It could occur through actual damage (collision or other impact), internal pipe rupture, or water entry through openings.

Both intact and damaged stability analyses take into account downflooding of water through openings in the deck or columns. For openings intended to be left open at all times (e.g. chain lockers) the intact stability should be sufficient to prevent water entry. Most openings are intended to be closed in heavy weather, either automatically or manually.

The early barge type mobile drilling units had some internal watertight bulkheads or other subdivision, but in the majority of cases there is no explicit criteria applied defining the extent of flooding to be tolerated. Most of the units did not have loadlines, so no regulatory limit on draft applied either.

Submersible units with bottle type legs also had subdivision and some flooding standard was usually applied for the afloat condition. Typically a one compartment standard was used with a constraint either on freeboard or angle after flooding. The same approach applied for semisubmersibles and the 1968 ABS rules called for a one compartment standard with positive freeboard after damage, including the static effect of a 50 knot wind. There was some confusion whether the standard applied to any one compartment or only compartments near the waterline. This was clarified in the 1973 edition of the rules to include one or more compartments, but only near the waterline. Multiple compartments are assumed flooded only if the watertight boundaries are too near the waterline, or each other.

All new MODUs are now designed to at least a one compartment damage requirement or a more stringent one. The static effect of a 50 knot wind is included, but there is no allowance for waves and motions in terms of freeboard to downflooding openings. Many flooding casualties where there is no damage can be traced to wave entry into multiple openings above the static waterline.

The vast majority of damage casualties to mobile drilling units are caused by the support vessels which are almost always in attendance. The present rules relating required damage to the waterline are therefore sensible. There are differences between regulators over the extent of damage which can be caused by these vessels. While the focus in present research is toward intact stability, efforts are underway to apply statistics to define probable damage location and extent. Such guidelines are already in effect for merchant ships.

As a result of the Ocean Ranger disaster, most designers feel that a one compartment flooding standard without reference to the waterline is necessary. This allows for ballasting errors as well as inadvertant flooding.

Much of the effort previously described relating to intact stability will find application for damage stability. As already noted the two topics are very much interrelated in terms of survivability of an offshore mobile drilling unit.

4.8 INSTRUMENTATION AND CONTROL

Early units typically had a central alarm panel which monitored the major items of rig equipment. With the exception of the ballast system, control was generally local, i.e. each piece of machinery was controlled at the machine.

The increased size and complexity of todays MODUs requires a more sophisticated monitoring and control system. The most advanced units use a microprocessor based, multiplexed distributed information processing system. The system provides for the pickup and distribution of measurement and control signals at remote locations on the unit and the display and manipulation of these signals at a central location. Every significant item of equipment is connected to the system so that all essential functions can be monitored and controlled from a central location.

This level of sophistication is not usually found on smaller units, which still use local control and conventional alarm panels.

Significant advances in instrumentation and control technology have resulted in increased safety and reliability of dynamic positioning systems. Automatic position keeping systems rely on underwater transponders and vessel mounted hydrophones to determine and maintain the vessels precise position. Advances in computer technology, and fully azmuthing thruster systems enable precise directional and thrust control to keep DP MODUs on station in severe environments.

Redundancy has been built into the most recent DP units in a number of ways. In addition to fully automatic control systems some operators make use of two additional back up systems. The first is a

riser angle positioning system which is designed to keep the unit in position by monitoring and maintaining a constant riser angle. The second backup is a manual joystick override which allows complete manual control.

Further safety measures are aimed at maintaining electrical generating and transmission capabilities in the event of damage to either system. Engine rooms are provided with fire resistant bulkheads separating the main generators. This allows partial electric generating capacity in the event of a fire in one portion of the engine room. Dual electrical transmission systems allow rerouting of electrical power in the event of damage to either system. These forms of protection are also known as "blackout" protection.

4.9 HARSH ENVIRONMENT PROTECTION

4.9.1 Cold Weather

Early offshore drilling units were designed for mild weather operating conditions and included no provision for cold weather conditions. As drilling units encountered increasingly hostile environments weather protection was provided as required. Piping was heat traced, heaters were provided in working areas, windbreak and enclosures were added. Newer designs incorporated these features along with insulation and more equipment for measuring environmental conditions. Present units have varying degrees of cold weather protection depending on their intended area of operation. The smaller units which intend to compete with jack-ups in temperate waters have minimal cold weather protection. The world class units, and those particularly intended for cold weather operation, have formalized operating procedures for dealing with ice and snow loads, iceberg contingencies, pack ice contingencies, and the parting of the anchor chain in emergencies.

The most recent designs for world class vessels operating in Arctic environments make use of advancements in materials technology. This includes the use of high tensile steel developed for use in cold temperature environments. An example of a drillship designed for cold weather operations is shown in Figure 8.

4.9.2 <u>High Current</u>

Drilling in areas subject to high current present special problems. To minimize the current forces on the marine riser a fairing is often employed to reduce the drag coefficient of the riser.

5. DESIGN PROCESS

The design process, including procedures, analysis tools, and mechanisms for change is discussed in the following sections. A review of design procedures is presented in Section 5.1, beginning with conceptual design and running through preliminary to final design. Figure 7 shows the basic elements of the design procedure. Section 5.2 discusses briefly some of the analytical techniques that are available to the designer at present. Section 5.3 comments on the basis for changes in design philosophy.

5.1 DESIGN PROCEDURES

The design of a MODU is an iterative process. The final product is a platform optimized to support industrial operations. A large effort by many participants is required. To arrive at this final result many variations and possibilities of configuration and structure are explored. Through an iterative approach, the best design for the particular task is developed.

The following will outline this procedure as applied in the design of a semisubmersible drilling unit. While the same general approach applies to drillships and jack-ups, the semisubmersible will be used for illustrative purposes.

5.1.1 Conceptual Design

Most major projects begin with a conceptual design phase. A conceptual design covers a fair range of capabilities and is a good starting point from which to develop the exact needs of a project.

The conceptual design phase comprises four major tasks as follows:

- Definition of basic operational parameters
- Initial sizing and configuration
- Stability and initial motions studies

- Review of results

Basic operational parameters include the intended area of operation, environmental constraints, desired payload and motions, and other design criteria. After these have been defined initial sizing and general arrangements follow. After initial sizing a preliminary weight estimate is made and stability and motions studies are performed. Finally a review of the results of this first iteration is made before beginning the next stage in the design process.

5.1.2 Design Basis

The next step is the preparation of a complete design basis. Operational parameters or criteria of the concept phase are carried forward to become part of the design basis.

Consideration of detailed operational requirements, classification and regulatory requirements, and technical design procedures serve to form the basis for design. Operational requirements derive from both the owner and environmental constraints. Classification and regulatory body requirements depend on the choice of a classification society and country of registry as well as on the vessel type, intended service, propulsion configuration, and other considerations. The technical approach for the different disciplines (structural, mechanical, electrical, and naval architectural) are formalized in an in-house design procedure.

5.1.3 Preliminary Design

With a defined and accepted design basis and a basic concept unit developed, the preliminary design can proceed. Six steps mark the preliminary design phase. These are as follows:

- Selection of basic arrangements
- Structural design and analysis
- Naval architecture

- Mechanical and electrical design
- Owner review
- Classification society/regulatory body approval

The selection of general arrangements is the first step in the procedure. From this the structural loading is calculated and a framing scheme developed in the structural design. Computer modeling of the basic structure and design loads yields preliminary member sizes and structural drawings from which the preliminary weight estimates are developed.

Naval architectural analysis proceeds based on the vessel configuration and weight estimates. Stability criteria are usually defined by the regulatory and classification considerations as well as specific owner requirements.

Damage stability defines the hull and column (in the case of semisubmersibles) compartment sizes. The remaining naval architectural tasks include motions analyses and downtime or operability studies.

Preliminary mechanical and electrical design include developing:

- System requirements and schematic diagrams
- Equipment arrangements
- Initial power and electrical load analysis
- Equipment weights

Upon completion of the technical design work in the preliminary phase a review of the results is made by the owner. Lastly, the preliminary design is submitted to the classification society and regulatory bodies for "approval in principle".

5.1.4 Model Testing

For a new configuration or for a vessel that differs significantly from other designs it is necessary to conduct model tests to verify loads and motions developed by analytical means. The following are the types of model basin and wind tunnel tests to be considered:

- Motion response
- Air gap/wave passing check
- Towing resistance
- Wind and current forces

5.1.5 Final Design

Upon approval of the preliminary design by the owner, classification society, and regulatory bodies, the final design begins. The final package is a set of documents (drawings and construction specifications) for classification/regulatory approval and defines the unit to be built. Shipyard bids are obtained using these documents.

The final design phase includes all of the same aspects as the preliminary design phase but in greater detail. Detailed arrangement drawings are based on the review of the preliminary arrangements.

The structural analysis is expanded and includes:

- Overall structural analysis
- Local member design
- Preparation of a "Strength Booklet"
- Fatigue analysis
- Redundancy analysis

Final naval architectural design results in the preparation of a "Hydrostatics and Stability Book". This is compiled from the results of the final intact and damaged stability analyses. A detailed

mooring analysis is peformed to confirm the mooring system capabilities. Final lightship weight and VCG estimates are made to determine the expected vessel payload capabilities. These results are usually included in the "Hydrostatics and Stability Book".

Mechanical and electrical final design results in the preparation of a good number of drawings and selection of equipment. Schematic and flow diagrams for all piping and cabling are prepared. Detailed routing and final pipe sizes are determined. The mechanical and electrical work also includes the selection of equipment such as pumps, valves, electrical distribution equipment and other components.

A construction specification is also prepared. The function of the construction specification is to define the material, equipment and workmanship required for the completed unit.

The majority of items involved in the final design must be reviewed and approved by either the classification society or regulatory bodies or both.

Further involvement by the designer often extends through the construction period with:

- o Review and approval of as-built drawings prepared by the shipyard.

- o Preparation of the Marine Operations Manual and Construction Portfolio for the vessel.

- o Participation in systems testing, sea trials, and the inclining experiment upon completion of the unit.

5.2 ANALYTICAL TECHNIQUES

Advances in design capabilities and analytical techniques have increased the safety and reliability of MODUs. The basic structural adequacy of state-of-the-art MODUs is ensured through:

- o Reasonable safety factors for design loads
- o Improved fatigue analysis capabilities
- o Structural redundancy
- o Ability to withstand collisions
- o Use of appropriate materials

The next three sections describe briefly the analytical techniques available to the present day designer and how they have been improved over the history of offshore drilling.

5.2.1 Strength

In the early days of offshore drilling with the converted barges, shallow water depths, and mild environment there was little strength analysis other than the operators eyeball estimation of whether or not the platform could support the load of the drilling equipment.

Today a complete structural analysis will run through a number of iterations throughout the design process. It will require the efforts of an engineering staff and a substantial computer budget perhaps running to six figures.

A modern strength analysis will include the following steps:

- o Establishment of design criteria
- o Load calculation

- Space frame analysis
- FEM check of structural details

The design criteria are based on the classification society and regulatory body rules where applicable, otherwise owner requirements or consideration of the service conditions to be encountered may govern.

Worst case loading conditions are determined for various stages in the units life such as: construction, launching, transit, operating, and survival conditions. The basic loads to be determined are as follows:

- Lightship (dead load)
- Consumables
- Hydrostatic loads
- Environmental loads
  - wind
  - wave
  - current
- Accidental loads

Space frame analysis of a mathematical model of the vessel structure includes both static and dynamic cases for semisubmersibles. In the case of drill ships and jack-up units a static or pseudo-dynamic analysis may be sufficient. All possible failure modes including yielding, buckling, progressive and accidental collapse should be checked. Deterministic or spectral analyses can be used.

Lastly, for the critical joints and connections, such as column to deck or column to pontoon for a semisubmersible, a coarse grid finite element analysis should be made. This allows a more detailed study of the force flow in these critical areas.

5.2.2 Fatigue

Improvements in theory and computer hardware over the past 20 years has greatly improved the designers ability to estimate fatigue lives for the various MODUs.

Fatigue failure is caused by cyclic loading of structural elements. From initial cracks present in the metal, fatigue stresses cause crack propagation and barring detection can cause failure. There are two basic methods of fatigue analysis available 1) Miner's Rule and 2) fracture mechanics methods.

Proper fatigue analysis includes consideration of all significant types of cyclic loading. These are analyzed for various conditions including transit and deep draft operating conditions. Cumulative damage bands are calculated on a long term distribution of stresses at critical points. This is accomplished through application of spectral analysis techniques where environmental data is input as a scatter diagram of sea state probabilities and directional probabilities considered. Critical point stresses at particular joints are calculated using empirical formulae. For more complex joints a finite element analysis or fatigue test experiment is required to accurately determine stress concentration factors (SCFs). SCFs relate the critical stress to the nominal stress in the member.

The fatigue damage curve (S-N curve) is different for each particular weld detail. Recent studies have been carried out to test tubular welded structures in order to determine their precise S-N curves.

Results of the fatigue analysis is used to ensure adequate fatigue life for all members as well as to point out the weaker members and joints. This information is used in the development of the in-service inspection program to monitor structural strength over the life of the unit.

5.2.3 Structural Redundancy

Some regulations now require a redundancy analysis to access the reserve strength of the unit. The purpose is to safeguard against collapse of the structure due to loss of a member or node. The cause can be from dropped objects, collision or fatigue failure. The failure of any member must not lead to a progressive collapse of the unit and the damaged rig must be able to sustain a reasonable severe storm in the working environment. In some cases, the assessment of the damage can be complicated, and a finite element method analysis or a structural model test may be necessary.

5.3 EVOLUTIONARY PROCESS

The previous sections of the report provided examples of gradual and dramatic changes in design philosophy as new applications and criteria were introduced for MODUs. This section summarizes the factors which have the greatest influence on the design process.

5.3.1 Functional Requirements

Sections 3 and 4 emphasized the gradual changes brought about by the extension of drilling into deeper water and more severe environments. In many cases designers extended or modified existing design to operate in slightly deeper water. Most designs reached a limit of extrapolation, where the basic configuration could no longer be utilized on a larger scale. The shift of operations from the Gulf of Mexico to the North Sea is a good example of designs reaching such a limit of extrapolation. As described earlier in the report, the semisubmersible concept was adopted as a totally new solution to the problem of operations in severe environments.

The design process discussed earlier is based on iterative procedures, therefore increased functional requirements generally lead to larger areas, weights volumes, and steel requirements until a particular configuration reaches a practical limit on proportions,

such as width or transit draft. When such a limit is reached, alternative concepts must be chosen. Thus the principal mechanism for evolution of MODU designs has been the changes in configuration brought about by increased functional requirements and environmental limits.

5.3.2 Operating Experience

Most designs are not truly optimized until operating experience is gained with the unit under both normal and extreme conditions. Equipment layouts and hardware are generally the areas most subject to change as operators' feedback is obtained. New designs often utilize substantially revised systems for mooring, handling of drilling equipment, and ships' services. Often these systems require 'de-bugging' in the field for the first unit of a new design. In contrast to changes in functional requirements, feedback from operators most often affects components, rather than the basic configuration of the unit.

5.3.3 Regulatory Influence

Over the years prior to 1981, regulatory influence on design has been gradual rather than significant. Most changes in regulations dealt with safety equipment, fire protection sytems, and communications sytems. Changes in regulations were often a reaction to the introduction of new technology rather than the result of any deficiency in a particular area.

In 1981 the Alexander Kielland accident in Norway initiated a complete review of regulations in effect for MODUs in Norway. As a result, major changes in stability, strength, and lifesaving equipment requirements were introduced for North Sea operations in Norway. These regulations made many existing design obsolete. Designers, recognizing that existing designs could not be modified economically to meet new regulations, adopted new configurations for semisubmersibles.

Other countries observed the development of the Norwegian regulations and the reaction of designers to such changes, and proposed further or similar changes to their own rules. A justification for this action was felt to be some designers and operators ready acceptance of the new regulations. In fact, most operators and designers believed the resulting regulatory changes were too severe, and could not be justified by operating experience. The debate on needed safety regulations continues in the International Maritime Organization (IMO), and also in various coastal states where offshore drilling exists.

5.3.4 The Record

Detailed accident records for MODUs have been maintained in the United States and in Europe for approximately 12 years. No attempt is made in this report to evaluate or interpret published results, other than to present the main conclusions from a recent project carried out in Norway, the MOPS Project (Ref. 18). This project concluded that MODU accident frequencies have been reduced over the years, and figures and statistics were presented in support of that conclusion. Figure 9 is extracted from Ref. 18 to show this trend.

6. FIGURES

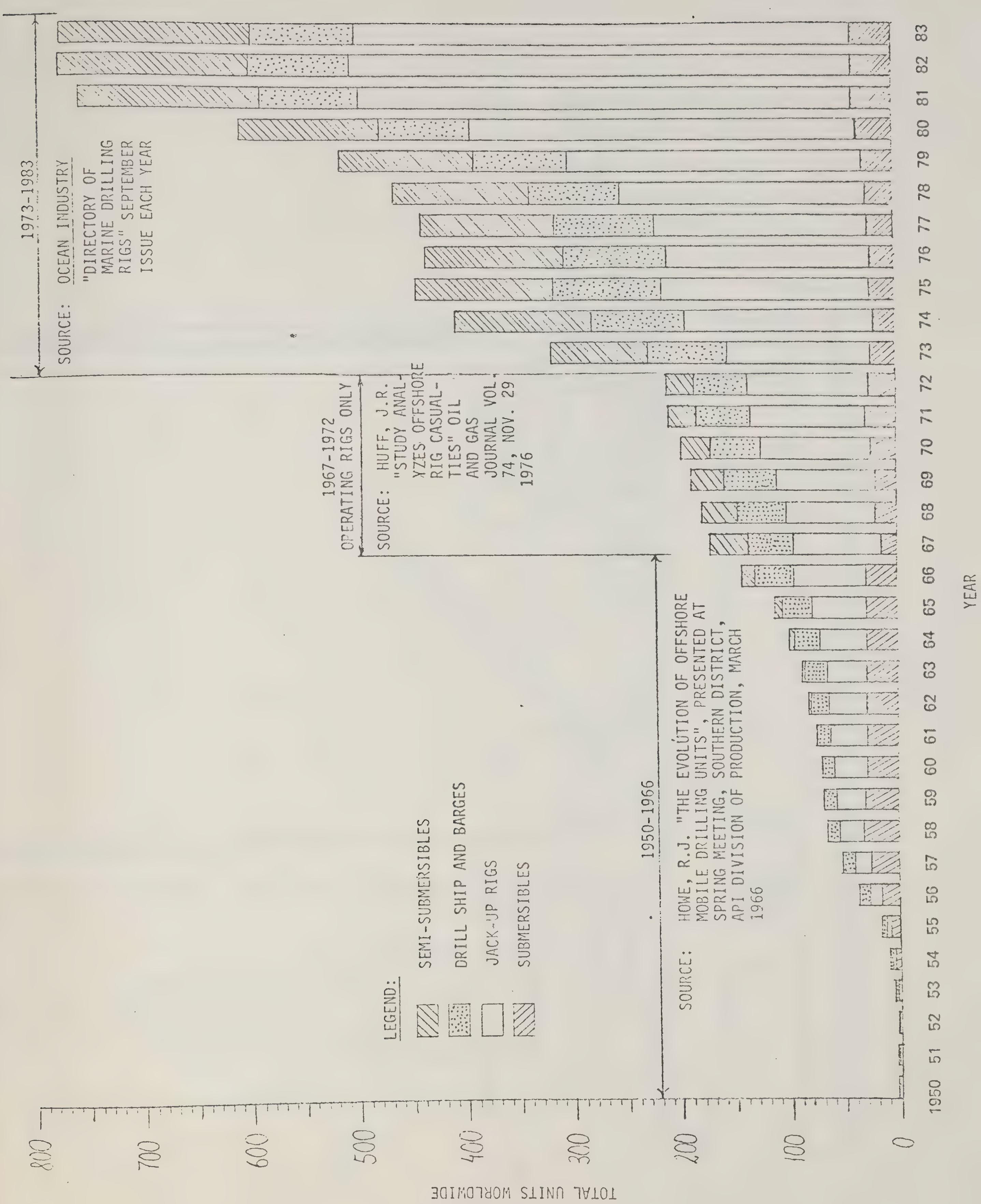

FIGURE 1

HISTORICAL GROWTH OF MODU FLEET

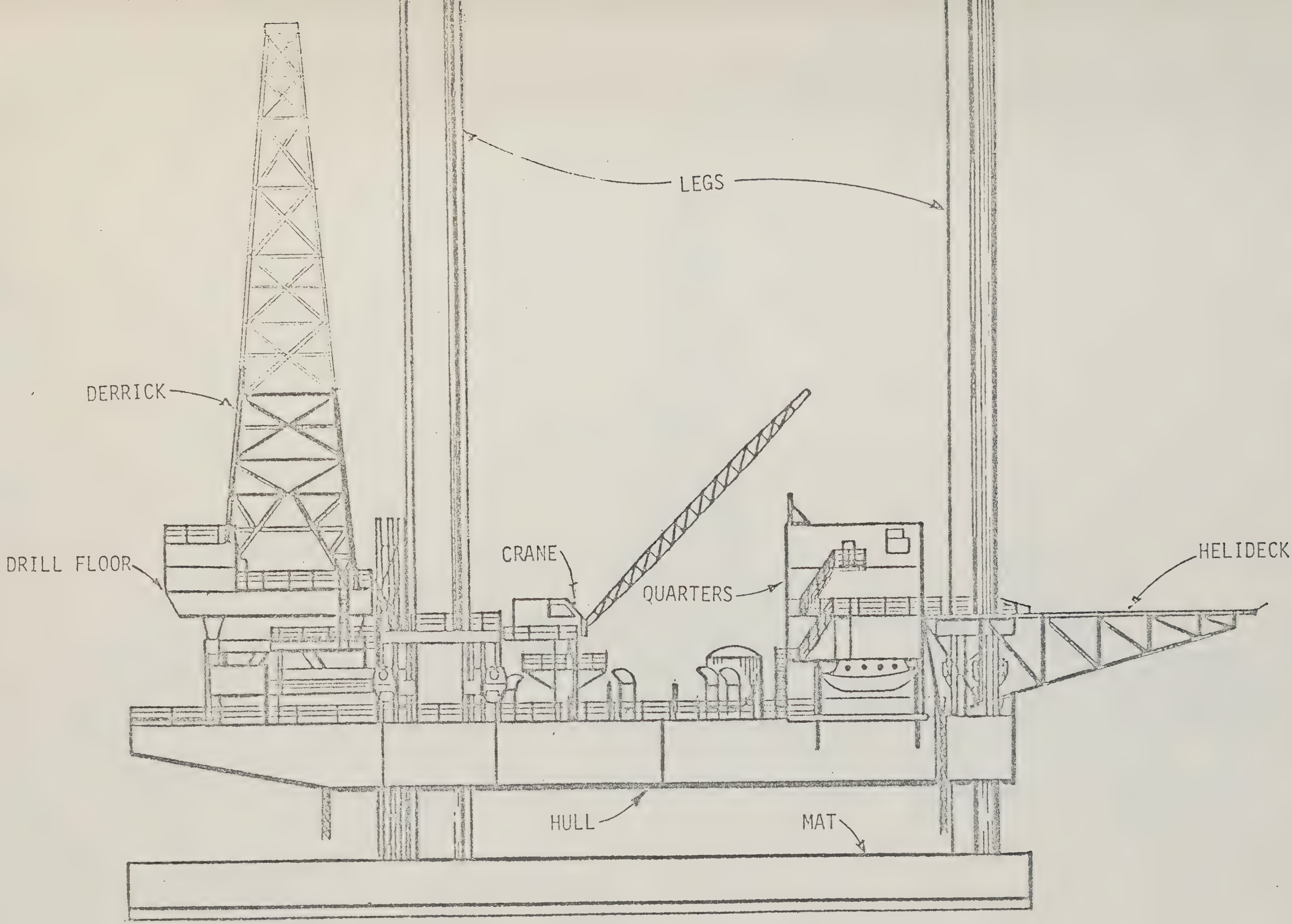

FIGURE 2
JACK-UP TYPE UNIT

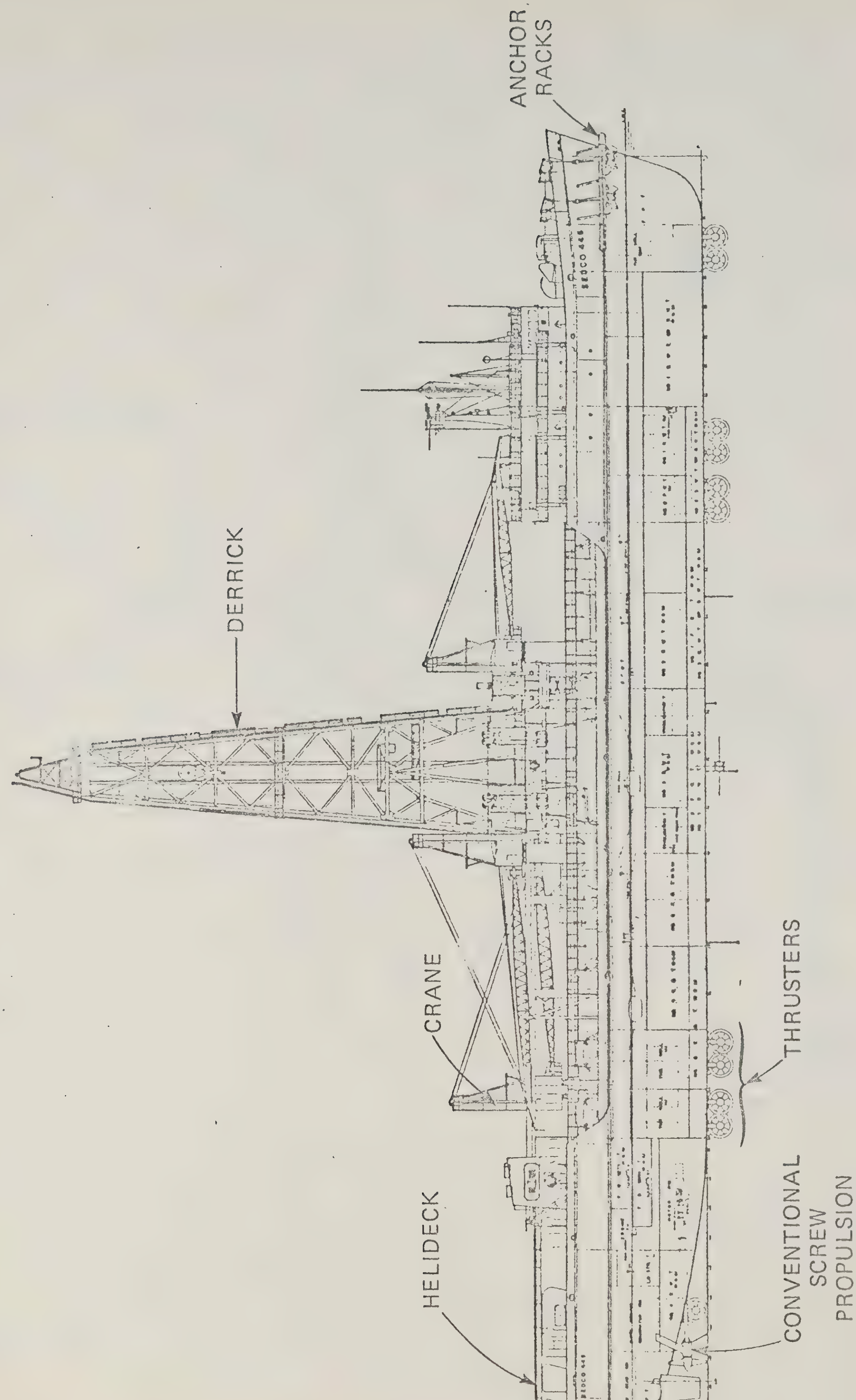

FIGURE 3

DRILLSHIP TYPE UNIT

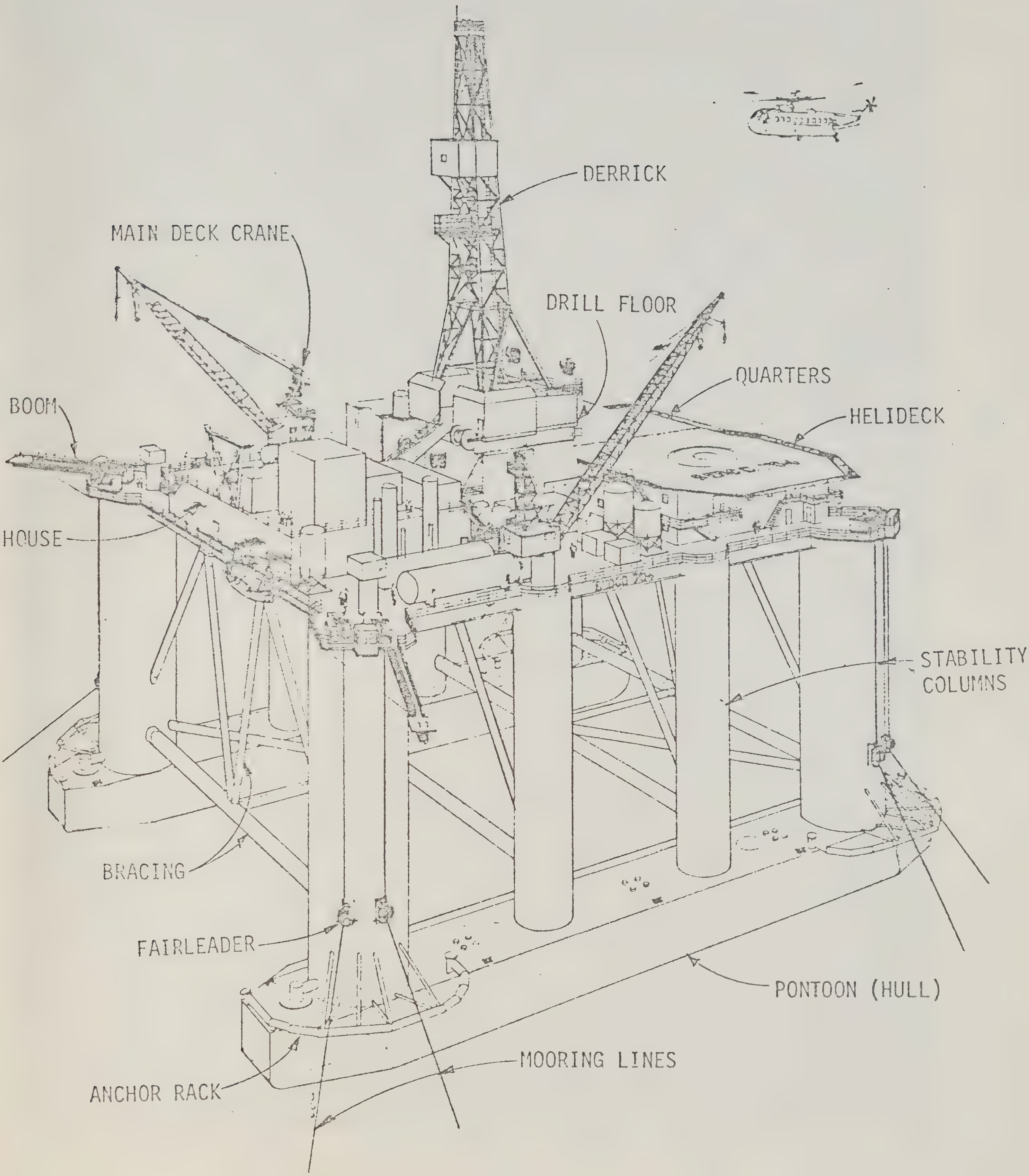

FIGURE 4

SEMISUBMERSIBLE TYPE UNIT

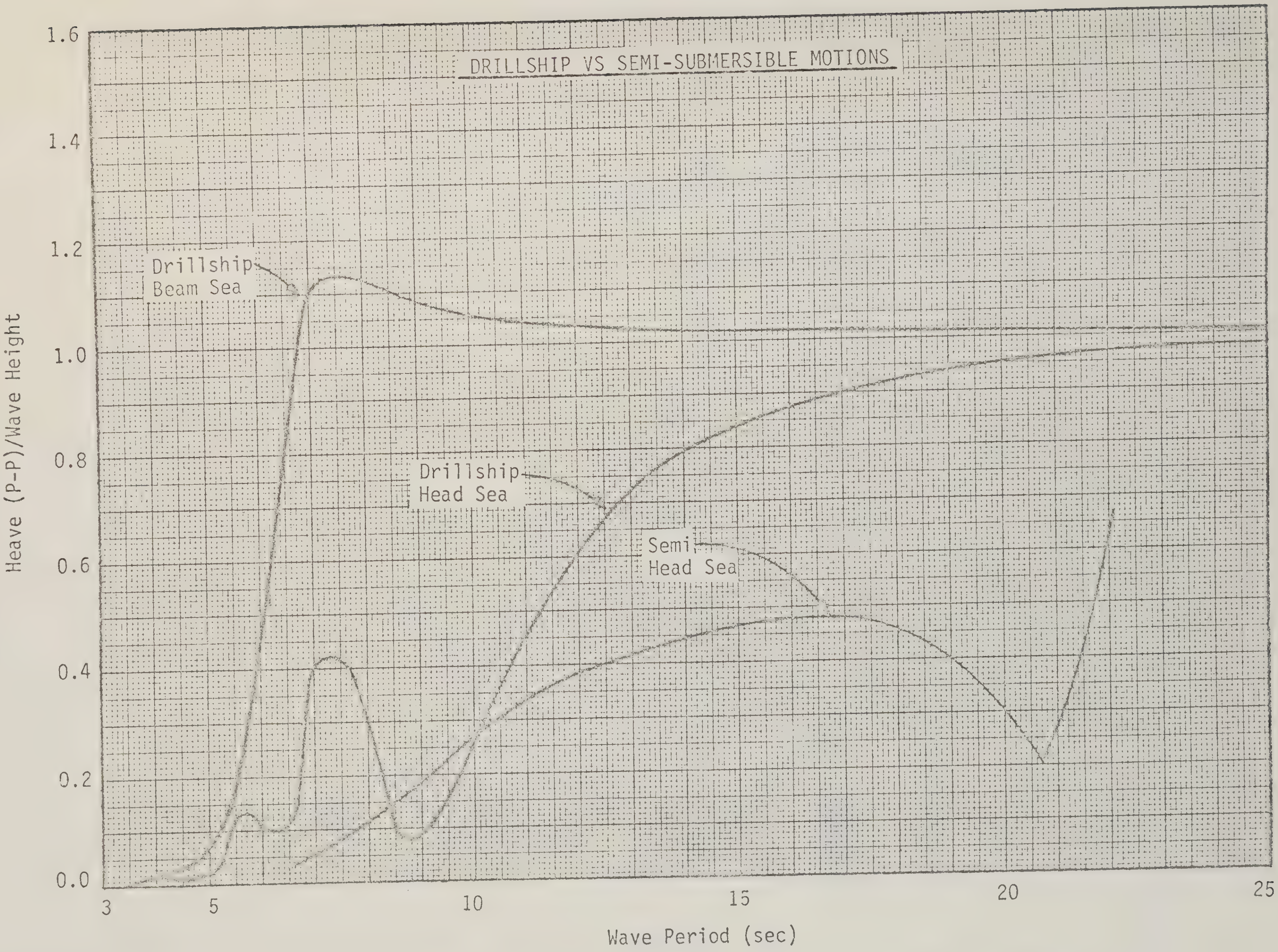
DRILLSHIP VS SEMI-SUBMERSIBLE MOTIONS
Drillship Beam Sea
Drillship Head Sea
Semi Head Sea
Heave (P-P)/Wave Height
Wave Period (sec)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
3
5
10
15
20
25

FIGURE 5

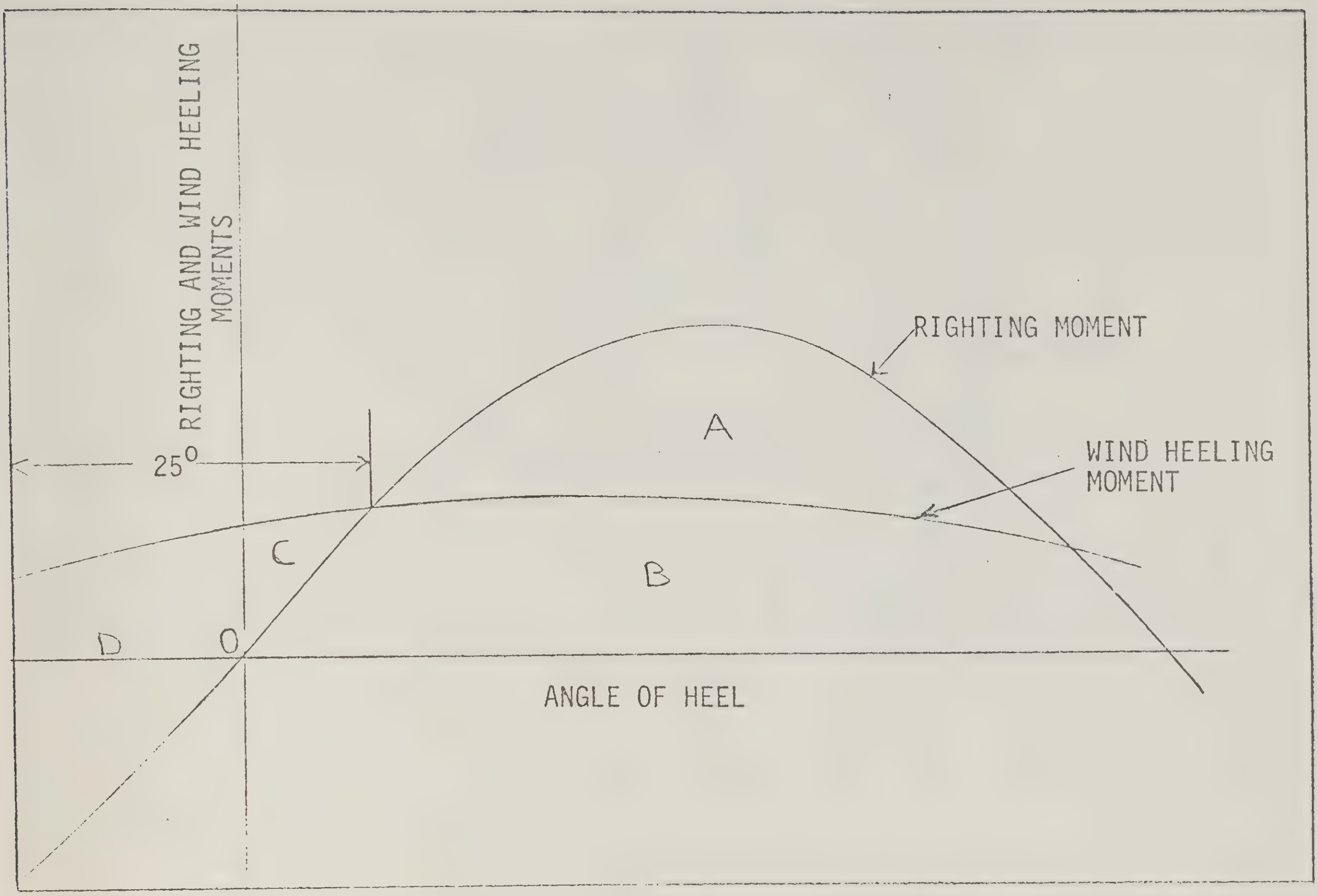

FIGURE 6

STABILITY - RIGHTING AND WIND HEELING MOMENTS

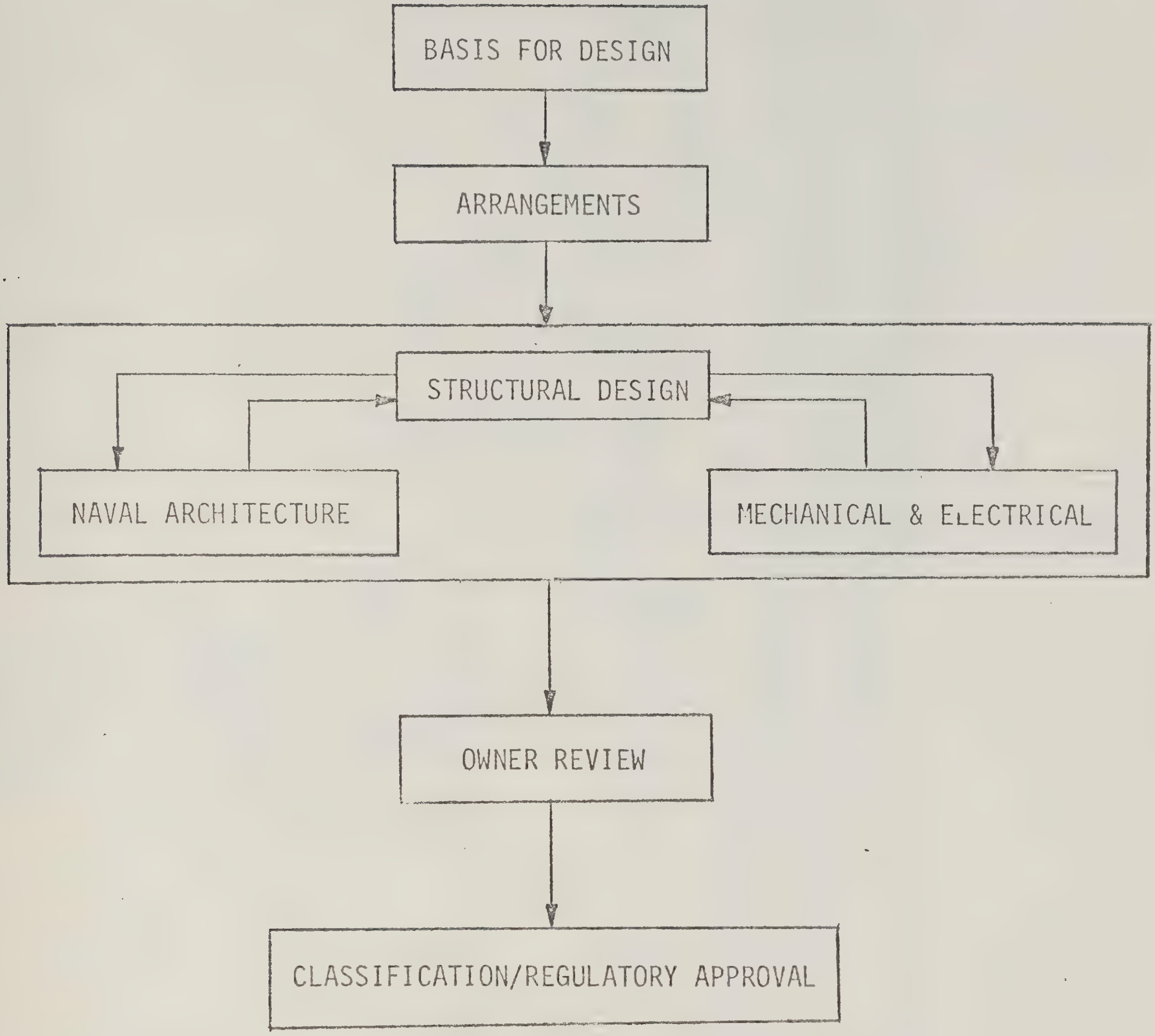

FIGURE 7

BASIC DESIGN PROCESS

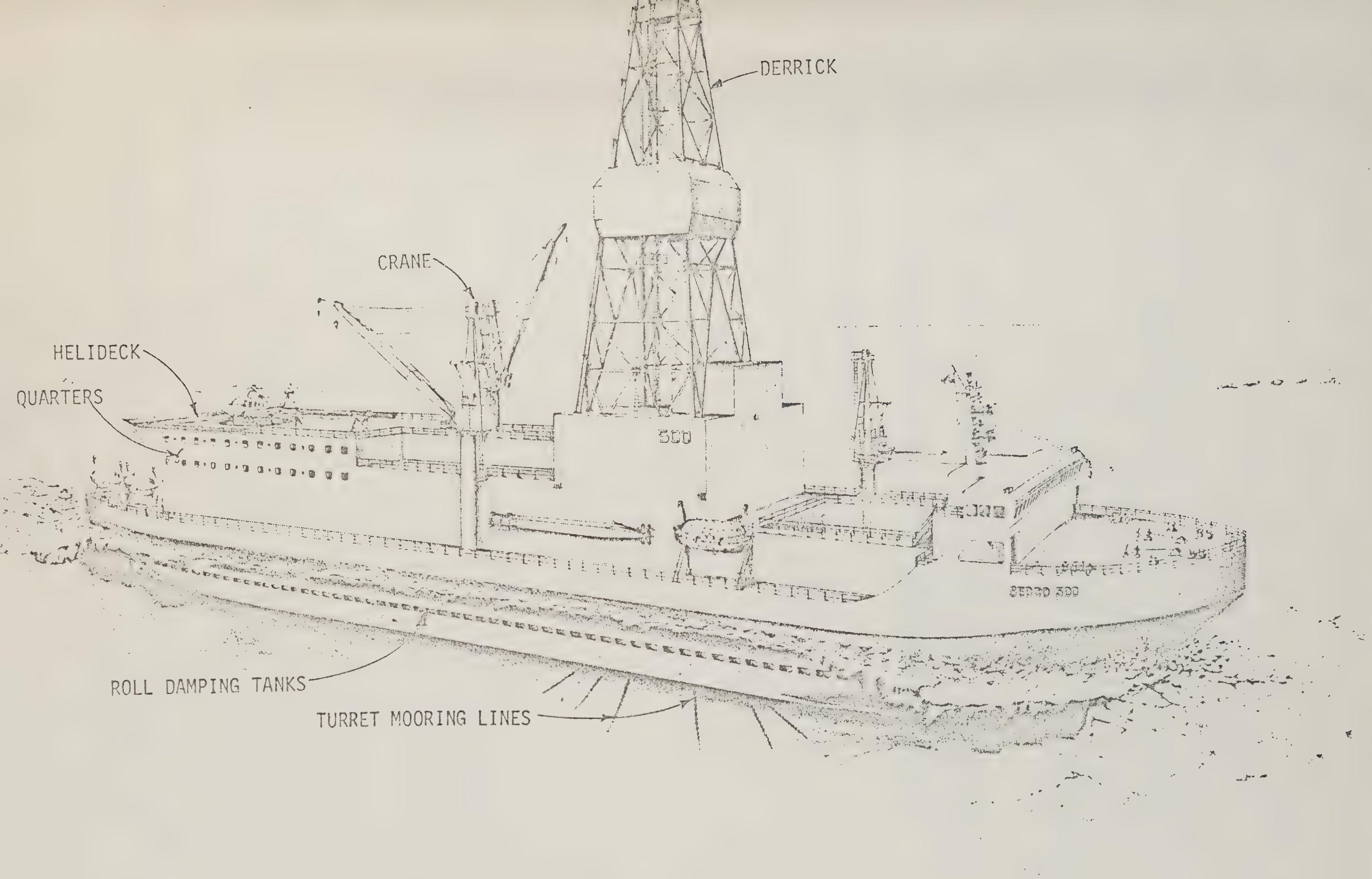

FIGURE 8

ARCTIC DRILLSHIP

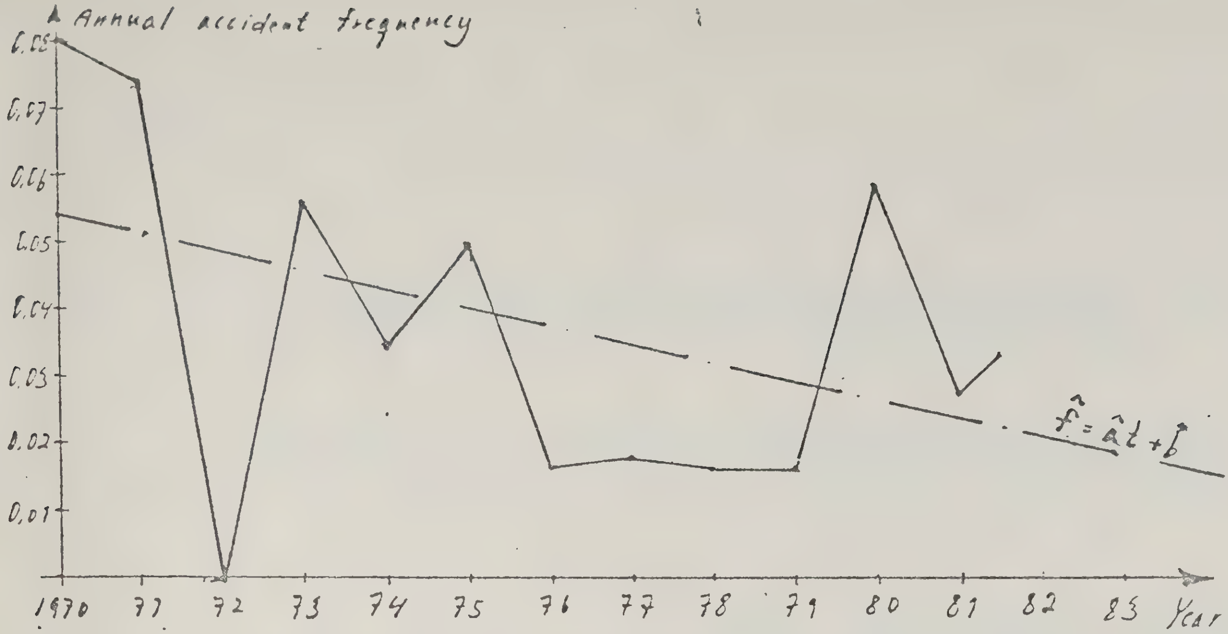

Fig. 3.1: Distribution of the yearly accidental frequency for semi-subs.

Linear regression analysis gives:

$$f = 2.7\times10^{-3} \times t + 5.3\times10^{-2}$$

Fig. 3.2: Distribution of the yearly accidental frequency for jack-ups

Linear regression analysis gives:

$$f = 8.0\times10^{-4} \times t + 2.0\times10^{-2}$$

FIGURE 9

ACCIDENT TRENDS
(Ref. 18)

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Appendix 8.1
Glossary of Terms

Blowout Preventer (BOP): A piece of hydraulically operated equipment located at the wellhead that is designed to prevent any accidental escape of oil and gas from the well.

Certificate of Fitness: The document issued by a certifying authority indicating compliance with all applicable regulations required for operation in a specific coastal state.

Certifying Authority (CA): Usually a government body or sometimes a properly designated substitute (such as a recognized classification society) that has the authority to grant to a vessel a certificate of fitness, provided that requirements of all regulations have been met.

Classification Society (CS): A professional organization that develops rules, reviews designs, and assigns a class for vessels.

Column: Large diameter structural and buoyant members that connect the deck and pontoons of semisubmersible units, as well as providing stability to the unit.

Derrick: A large load-bearing truss work structure used to support the drill string during drilling operations.

Drill-Barge:	A non-self-propelled barge complete with machinery and equipment necessary for drilling a well offshore.
Drillship:	A self-propelled mobile floating offshore structure of conventional ship shape.
Drillwater:	Fresh water used for mixing mud and also for cooling of machinery.
Drilling Rig: or Drilling Unit	Any floating, mobile platform (ship, barge, semisubmersible, etc.) used for exploratory drilling offshore.
Jack-Up Rig:	Also know as a self-elevating unit. A mobile floating offshore structure that, when on site, is supported by legs lowered to the seafloor, with the hull raised out of the water.
Land Rig:	The machinery and equipment necessary for drilling a well on land.
Mast:	Similar to a derrick except hinged to allow lowering onto the deck of the MODU.
Mobile Offshore Drilling Unit (MODU):	A Vessel capable of performing drilling operations offshore.
Mud:	The dense circulating fluid made up of dry minerals and water or oil that is pumped down the drill string and back to the surface to carry the cuttings from the hole. In addition the column of fluid counteracts reservoir pressure when it encounters a find.

Pontoons: The lower hulls of a semisubmersible drilling rig, which are major displacement members.

Regulations: Those requirements concerning design, construction, and operations of units, promulgated by regulatory bodies.

Regulatory Body: A government body that creates legislation concerning the safety of offshore structures.

Rules: Those guidelines, standards, and criteria for design, construction, and operation that are required for registration of class by a classification society.

Scouring: For a bottom supported unit washing away of the soil around the legs or submerged hull due to current or waves.

Semisubmersible: A mobile floating offshore structure consisting of a raised deck supported by buoyant columns, which are connected to lower hulls or pontoons. Also known as a column-stabilized drilling unit.

Subsea Completion: Installation of wellhead and certain production equipment on the seabed for a producing well.

Submersible: A shallow water offshore drilling structure with several compartments that can be flooded to cause the structure to rest on the seafloor while drilling.